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OD 18413A
VOL II

HUMAN FACTORS DESIGN STANDARDS FOR THE FLEET BALLISTIC MISSILE WEAPON SYSTEM

VOLUME 2 DESIGN OF EQUIPMENT

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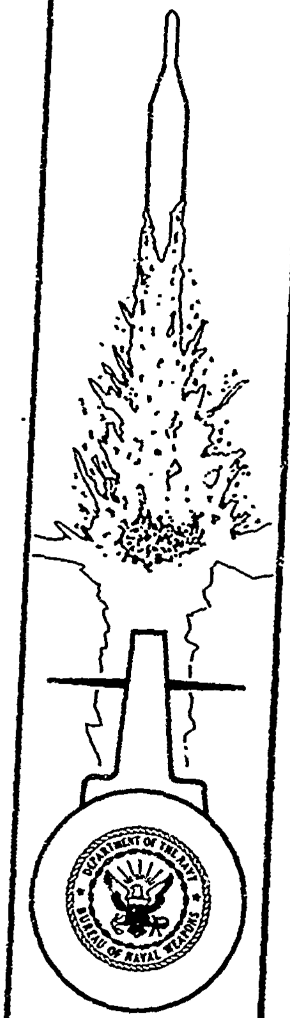

HUMAN FACTORS DESIGN STANDARDS FOR THE FLEET BALLISTIC MISSILE WEAPON SYSTEM

AUGUST 1962

VOLUME 2 DESIGN OF EQUIPMENT

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IN REPLY REFER TO

NAVWEPS OD 18413A

HUMAN FACTORS DESIGN STANDARDS FOR THE FLEET BALLISTIC MISSILE WEAPON SYSTEM

1. OD 18413A is promulgated for the information and guidance of all military, government, and contractor agencies participating in the development of the Fleet Ballistic Missile Weapon System. The purpose of this publication is to provide human factor guidelines for the design of the FBM Weapon System and its components. It is published in two volumes: Volume 1, Design of Systems; Volume 2, Design of Equipment.

2. Consideration of the guidance and information provided in this document is mandatory in new designs for FBM Weapon System equipment and components scheduled for installation in SSB(N) 616 and later class submarines. Notice of errors, omissions, and corrections should be submitted to the Special Projects Office (Sp2012), Department of the Navy, Washington 25, D. C.

3. OD 18413A supersedes all previous issues of this publication which should be destroyed. Evaluations of Control-Display Components, included in previous issues, have been discontinued.

Levering Smith

LEVERING SMITH
Technical Director

PREFACE

The basic objective of this handbook is to provide special assistance to system and component engineers and human factors specialists in performing those portions of their engineering activities which may result in the specification or design of hardware to be operated and/or maintained aboard FBM submarines. The principles or guidelines in the handbook are based upon compilation of research findings and logical analysis, and are expressed in terms which permit direct engineering application.

As a matter of convenience, the handbook is being published in two volumes. Volume 1, "Design of Systems," contains Sections 1 and 2 of the handbook and provides a basis for establishing and evaluating alternative system and subsystem concepts with respect to man-machine requirements, capabilities, and trade-offs. Volume 2, "Design of Equipment," contains Sections 3 and 4 of the handbook and presents information on which to base the selection, utilization, and design of equipment to enhance human operation and maintenance activities and thus achieve improved system performance and availability. The two volumes will generally be used at different stages of system and subsystem definition.

Section 3 of this volume contains human factors considerations and guidelines to be used in the design of FBM equipments for operation. This section of the handbook should be applied after reasonably confident decisions have been made about the control and display requirements for the particular equipment undergoing design and its relationships to other equipments in the FBM system as discussed in Volume 1 of the handbook.

Section 4 of this volume contains human factors considerations and guidelines to be used in the design of FBM equipments for maintenance. This section of the handbook should be applied at the time when maintenance concepts are being formulated and reliability-maintainability trade-offs are being made, when modular packaging of circuits is being considered, and when technical manuals are being planned or developed and troubleshooting procedures formulated. Reference to Section 3 should be made whenever control and display requirements for maintenance are met.

ACKNOWLEDGMENTS

This handbook could not have been prepared without the continued encouragement and support of Vice Admiral R. F. Raborn, Rear Admiral Levering Smith, Mr. J. B. Buescher, and especially Mr. Solomon Burg of the Special Projects Office. In addition, the valuable assistance of Dr. J. Briggs, Nortronics Division, North American Aviation; Dr. J. Wissel, Missiles and Space Division, Lockheed Corporation; Dr. R. Wiencke, Heavy Military Electronics Department, General Electric Company; Dr. W. Blair, Electric Boat Division, General Dynamics Corporation; Dr. M. Katz, U.S. Naval Training Device Center; and Mr. G. K. C. Hardesty, U.S. Naval Engineering Experimental Station in reviewing portions of the handbook is gratefully acknowledged.

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CONTENTS OF SECTION

This section of the handbook+ contains human factors guidelines to be used in the design of FBM equipment for monitoring and operation by personnel. Four categories of hardware are considered: displays, controls, interior communication equipment, and control and display panels and consoles. Each of these categories is considered individually in this section and will be described briefly at the outset.

I. Displays

This subsection includes: (1) descriptions of the various types of display techniques and hardware which are available and are considered to be applicable to the display requirements of the FBM equipment; (2) guidelines for the selection and utilization of specific types of display components; and (3) guidelines for the design of displays to be used both to evaluate components which are available and, where suitable ones are not available, to provide human factors criteria for the design of components.

II. Controls

This subsection contains information similar to that provided for displays. It includes descriptions of the various types of controls which are available, guidelines for their selection and utilization, and guidelines for their design.

III. Interior Communication Equipment

This subsection includes: (1) descriptions of the naval classification of interior communication equipment; (2) guidelines for their selection and placement; and (3) some guidelines for their design.

IV. Panels and Consoles

This subsection includes: (1) descriptions of the various panel construction and illumination techniques which are applicable to shipboard use; (2) information on the physical dimensions of personnel related to reach, vision, and space requirements; (3) arrangement of control and display components and their method

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+Original issue, February 1960; revised, August 1962.

of operation; and (4) guidelines for selection or design, where required, of operator support equipment such as seats and back rests.

The design of control and display panels and consoles cannot be considered in isolation from the other aspects of design which must be undertaken at this time. These include the development of operating procedures, the control of environment (particularly the lighting under which the panels and consoles will be operated), the design of equipment for maintenance, and the selection and training of personnel.

The utilization of human factors specialists to assist in the application of this section of the handbook is desirable. Since many compromises must be made throughout the design cycle, such specialists should be available to assist the design engineers in recommending or evaluating any "trade-offs" which may be required among human factors, engineering, equipment or component availability, and the many other factors which ultimately determine the design of the system and its equipments. This handbook provides human factors guidelines that can be used both by the human factors specialist and by the design engineer; however, it cannot, by itself, insure the judicious application of these guidelines to the specific design situation.

I. DISPLAYS

1. Description

Displays can be classified in terms of: (1) the form in which the information is presented; and (2) the types of hardware which are used. Both of these classifications will be discussed; however, because of hardware orientation of the handbook, emphasis will be placed on the latter.

The classification of displays on the basis of the form in which the information is presented can first be categorized by the sense modality involved: vision or audition. (Other categories exist, but are unimportant for the design of control and display hardware.) Vision is of most importance in the design of displays; audition is somewhat less important.

Visual displays can be classified on the basis of the level of abstraction of the information they present, i.e., symbolic and pictorial. In general, although these terms are not mutually exclusive or completely accurate descriptions, the term symbolic is used to describe displays which present alphanumeric information or involve the presence or absence of signals -- for example, indicator lights, digital and word readouts. The term pictorial is used to describe displays which provide more realistic representations of physical or spatial relationships -- for example, radar displays or miniature representations of equipment showing location and functions of parts. Pictorial displays are used more often than symbolic displays in situations that involve the movement or control of vehicles -- for example, plotting of ship or aircraft movements on status boards or the steering of vehicles.

Visual displays also can be classified in terms of their qualitative or quantitative aspects. The term qualitative is used to describe displays which signify the existence or nonexistence of a condition or object -- for example, indicator lights or certain types of cathode ray tube displays. The term quantitative is used to describe displays which provide some type of measurement readout -- for example, meters or gages with calibrated scales and pointers. All numeric displays are not quantitative, since the numerals may not apply to the measurement of a quantity -- for example, "Missile Firing Order."

Auditory displays may be classified on the basis of whether they provide an abstract signal, such as a buzzer or bell, or whether they involve the transmission of verbal information, such as a telephone or an announcing system.

Categories of visual and auditory displays which are used, or have potential application, in the FBM system are described below. Components not discussed, such as large status displays, have been omitted because they do not have direct relevance to the design of control and display equipment for the FBM system.

1.1 Visual Displays

The types of visual displays discussed in this subsection include the following:

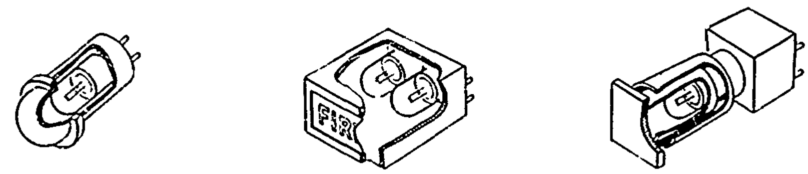
a. Indicator lights
b. Digital and word readouts
c. Scalar displays
d. Cathode ray tube displays
e. Printers
f. Recorders

1.1.1 Indicator Lights

Indicator lights are devices which are used to present qualitative and discrete information by means of controlled light sources. The illumination of a lamp or lamps behind a translucent display surface or change in color is used to indicate status of equipment, function being performed, or action required. Indicator lights may be combined with push-button switch units.

1.1.1.1 Single-Status Indicator Lights

Single-status indicator lights provide single, discrete, and positive indications by single-color illumination of display areas. These units may also be combined with push-button switches. A single-status display of this type may use a single miniature lamp, as for a pilot light, or several lamps. Banks of small units of this type may be used as binary or digital readouts. Blown-fuse indicators may also be classified as single-status displays. (Fig. 3-1)

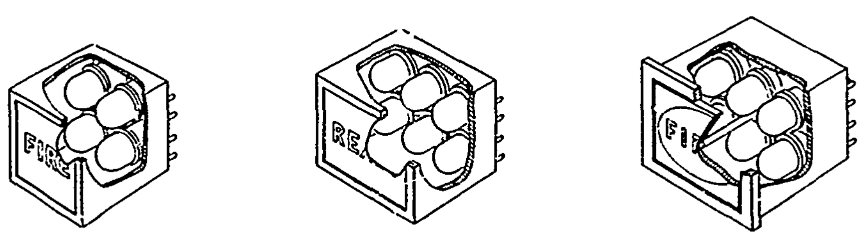


Pilot   Legend   Push button

Fig. 3-1. Single-status indicator lights.

1 1.1.2 Multiple-Status Indicator Lights

Multiple-status indicator lights provide as many as three discrete and positive indications by means of color change within a single display field. These units may or may not be combined with push-button switches. Multiple-status displays of this type may use various combinations of lamps and color filters, the number and position of such elements being determined by both equipment engineering and human factors criteria. (Fig. 3-2)



Two-color legend   Three-color legend   Push button

Fig. 3-2. Multiple-status indicator lights.

1.1.2 Digital and Word Readouts

Digital and word readout devices are used to transmit information by means of alphanumeric characters, words, or symbols.+ The distinctive characteristic of such devices is the time-sharing of a single display area for the presentation of information.

1.1.2.1 Sequential Access Displays

Readout displays which have a fixed relationship between characters and hence permit only a sequential presentation are termed sequential access displays. In such devices, images are usually imposed on drums or tapes which are interlocked by a mechanical linkage with similar units in the same module; hence, when proceeding from one representation to another, all intermediate values must be traversed. Examples of sequential access displays include counters, back-lighted message belts, and wheels. Only counters are discussed here, since the other types are commonly used as random access displays.

1.1.2.1.1 Counters

Counters are the most common type of sequential access display. They are electromechanically or mechanically operated displays which are generally used to provide exact numerical readout of information that is essentially continuous. A number of drums, around whose periphery digits from 0 to 9 have been imposed, are aligned axially in the same module and are linked together in a 10:1 ratio so that one revolution of the units drum drives the tens drum ahead one digit, one revolution of the tens drum drives the hundreds drum ahead one digit, etc. (Fig. 3-3)

1.1.2.2 Random Access Displays

Readout displays which do not have a fixed relationship between characters and hence permit a selection of data to be displayed in any order are termed random access displays. In general, such devices require

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+This discussion is limited to the relatively small devices for displaying alphanumeric information. Cathode ray tube displays can also handle alphanumeric information, but are discussed separately under that heading.

that a separately coded signal be used for each character. Although displays of this type with a capacity of as many as 64 different symbols are available at the present time, most generally used random access devices have a capacity of from 10 to 16 signals, including the digits from 0 to 9 and several additional signs. Specific types of random access displays include segmented matrices, gas tubes, edge-lighted plates, projection displays, and back-lighted belt displays.

1.1.2.2.1 Segmented Matrices

Segmented matrices are random access displays in which alphanumeric characters are formed by the independent illumination of individual segments that have been incorporated in one plane of a single matrix. The segments may be illuminated by incandescent, neon, or electroluminescent lamps, the characters appearing as dotted- or broken-line figures against a contrasting dark background. A logic circuit can be used which will decode binary information and energize appropriate display segments. Character legibility is improved by increasing the number of segments available (the greatest number of segments available at the present time is 21, which are afforded by the use of electroluminescent devices). (Fig. 3-4)

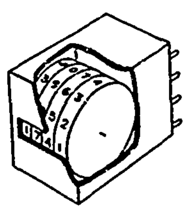


Fig. 3-3. Electromechanical counter.

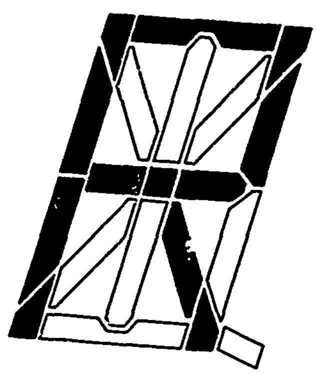


Fig. 3-4. Segmented matrix.

1.1.2.2.2 Gas (Cold Cathode) Tubes

A cold cathode tube contains a neon tube in which a number of independent (usually about 10) electrodes shaped like digits, letters, or symbols are arranged in depth from the viewing surface of the unit. Activation of each electrode provides an orange-red glow, making readout data visible to someone looking at the viewing surface (located on the top or at the side of the tube, depending upon the design of the component). Legibility of rearward characters is impaired because of the presence of other characters in front of them; also, viewing angle is restricted because planes on which characters appear are recessed from the face of the tube. (Fig. 3-5)

1.1.2.2.3 Edge-Lighted Plates

Edge-lighted plates consist of transparent plastic plates, arranged in parallel and in depth behind the front of the display unit, on which have been engraved the desired messages or symbols. Such displays are individually edge-lighted by incandescent lamps; messages may be illuminated in color. Impairment of character legibility and restriction of viewing angle, as noted for cold cathode tubes, are characteristic of edge-lighted plates. Also characteristic is the possibility of excessive cross-talk among various plates as a result of light spillage caused by the illumination of a single character. (Fig. 3-6)

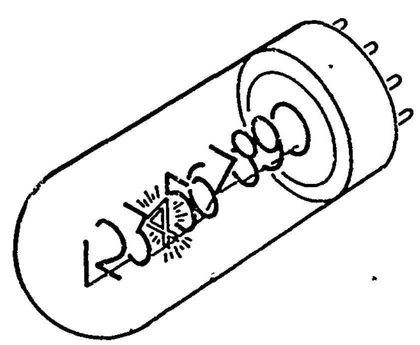


Fig. 3-5. Gas tube.

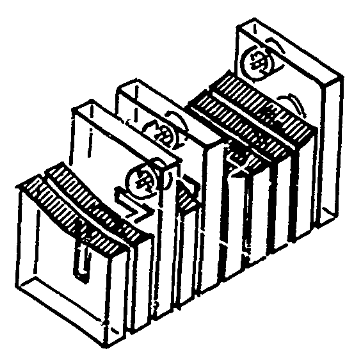


Fig. 3-6. Edge-lighted plates.

1.1.2.2.4 Projection Displays

Projection displays utilize the principles of light projection in combination with artwork transparencies or sliding templates for the random presentation of words, numerals, symbols, etc., on a common display screen. Such devices may consist of a number of miniature optical systems packaged in a single unit or of a single optical system using sliding templates for light interference. The image brightness of such displays ranges from moderate to low. Moreover, optical centering of lamp filaments may be required when units are installed or repaired. (Fig. 3-7)

1.1.2.2.5 Back-Lighted Belt Displays

This type of display employs a motor-driven continuous belt on which the character spaces, usually up to 64, are provided. These devices are capable of binary coding, data storage, and electrical and visual readout. One character at a time is positioned in the viewing window; therefore, multiple units are required to form a message or multi-digit readout. The tape background is opaque, and the transparent characters on it are back-lighted. (Fig. 3-8)

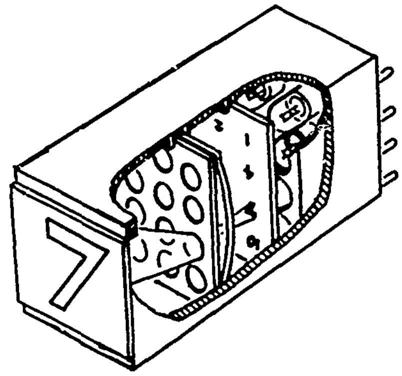


Fig. 3-7. Projection display.

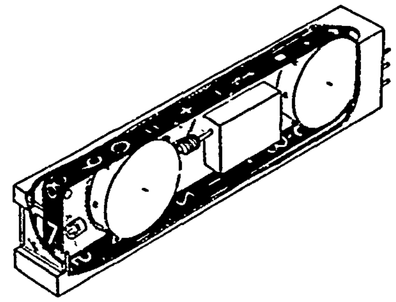


Fig. 3-8. Back-lighted belt display

1.1.3 Scalar Displays

Scalar displays employ graduated scales in conjunction with some indexing element such as a pointer, hairline, column of mercury, bubble, etc. to display quantitative (and, in some cases, qualitative) information. In such displays, the indication of change may be shown by the motion of either or both the scale and/or the indexing element. Components in this category include electrical indicating instruments, mechanical gages, and integral dials or straight scales which may be part of a larger display system (e.g., a recorder). (Figs. 3-9, 3-10)

1.1.3.1 Moving-Pointer Fixed-Scale Displays

These scalar displays use moving indexing elements and may be either circular or straight in configuration. The length of exposed pointer and the movement of the pointer facilitate check and qualitative reading. Use of vertical or horizontal straight scales make it possible to obtain a higher packing density on crowded panels than would be possible if circular or curved scales were used.

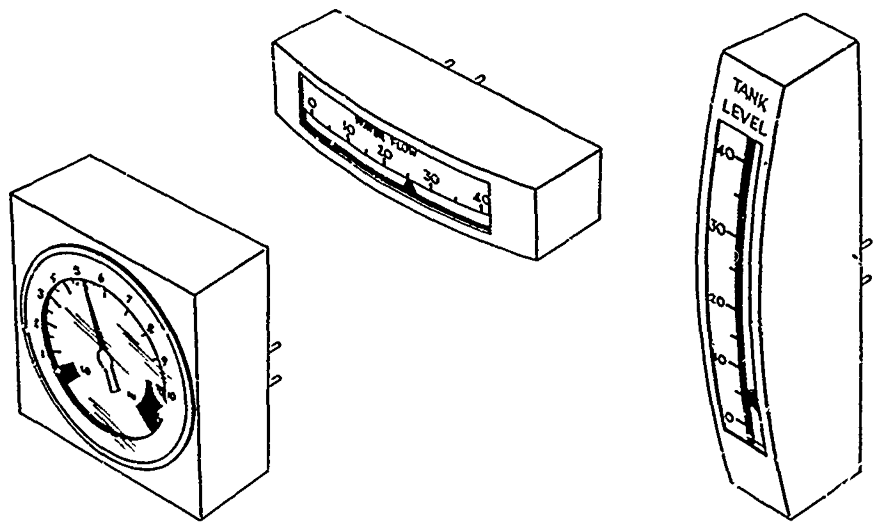


Fig. 3-9. Moving-pointer fixed-scale displays.

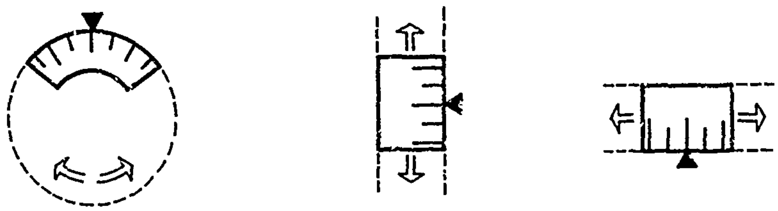


Fig. 3-10. Fixed pointer moving-scale displays.

1.1.3.2 Fixed-Pointer Moving-Scale Displays

These scalar displays use fixed indexing elements and may be either circular or straight in configuration. They are suitable for quantitative, but not qualitative or check reading. Except for heading indicators, these displays need have only a portion of the scale exposed, which allows a large range of values to be presented in a limited exposed panel space.

1.1.4 Cathode Ray Tube Displays

Cathode ray tube (CRT) displays are devices which utilize electron beams to portray electrical phenomena on a fluorescent screen. Representation of selected phenomena is accomplished by electrostatic or magnetic deflection of the electron beam in accordance with selected voltage or current waveforms.

In general, there are three classes of information which are commonly displayed on CRT displays:

a. Direct representations of electrical parameters such as waveforms, bargraph displays, or the outputs of analog computers.

b. Presentation of alphanumeric information.

c. Representations of objects in space, such as television, radar, or sonar presentations.

1.1.4.1 Radar Displays

The following types of installations are typical of CRT displays which are used for radar applications:

1.1.4.1.1 A-Scan

The signal is deflected vertically from the horizontal sweep path when a return is received. The distance from the start of the sweep to the signal is an indication of the range of the reflecting object. The magnitudes of the vertical deflections indicate the relative strengths of the signals.

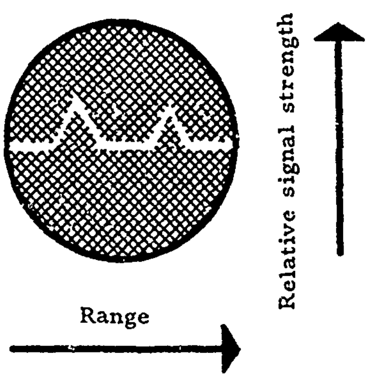


Fig. 3-11. A-scan radar pattern.

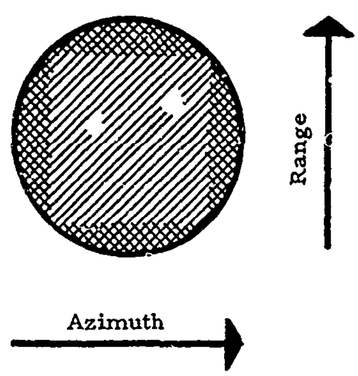


Fig. 3-12. B-scan radar pattern.

1.1.4.1.2 B-Scan

Azimuth is presented as a horizontal deflection of the cathode ray beam, and range is presented as a vertical deflection. The vertical scan begins as the pulse is transmitted; when a signal returns, its azimuth and range can be read from the display. An inherent disadvantage in such a display is that scope interpretation is made difficult by the spatial distortion that results from the use of coordinates. (Fig. 3-12)

1.1.4.1.3 C-Scan

The C-scan display is similar to the B-scan display except that the vertical axis displays altitude instead of range. (Fig. 3-13)

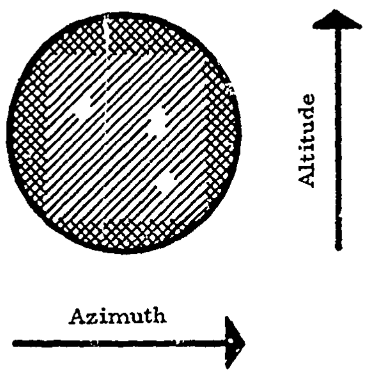


Fig. 3-13. C-scan radar pattern.

1.1.4.1.4 F-Scan

Azimuth error is plotted horizontally and elevation error vertically. Electronically presented crosshairs on the scope assist in bringing the system to bear on the target. (Fig. 3-14)

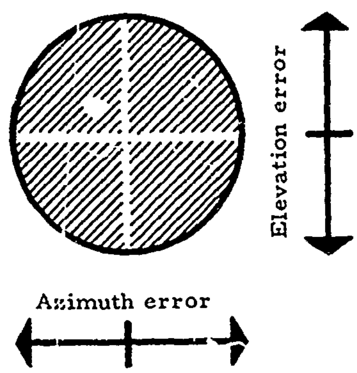


Fig. 3-14. F-scan radar pattern.

1.1.4.1.5 PPI-Scan

Range and azimuth are plotted in polar coordinates. The signal appears as a spot at a radial distance from the center of the display proportional to range. The position of the signal with respect to the angular location of the scan line corresponds to the azimuth of the target. The intensity of the signal corresponds approximately to the strength of the return. (Fig. 3-15)

1.1.4.1.6 Sector Scan

PPI-scan is used in a particular section in order to concentrate search or tracking in one enlarged portion of the display. (Fig. 3-16)

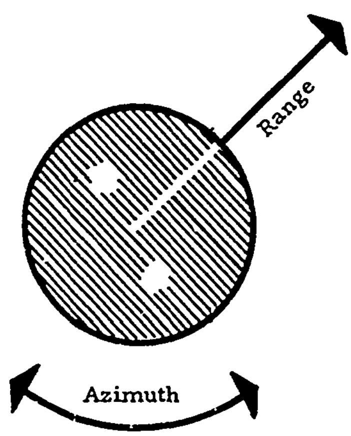


Fig. 3-15. PPI-scan radar pattern.

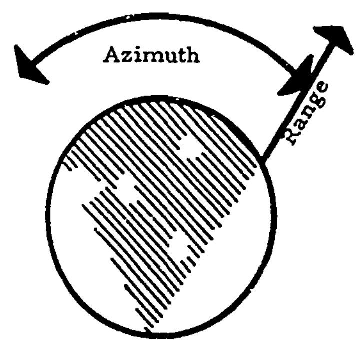


Fig. 3-16. Sector-scan radar pattern.

1.1.4.2 Alphanumeric and Pictorial Displays

The characteristics of the CRT make this type of display suitable as an output device for computer or other electronic control applications. For example, CRT's may be used to display alphanumeric data or pictorial information (e.g., a closed-circuit television). Special electronics is required to

generate symbols and other data formats; however, mechanical overlap can be used to simplify the internal control electronics. (Fig. 3-17)

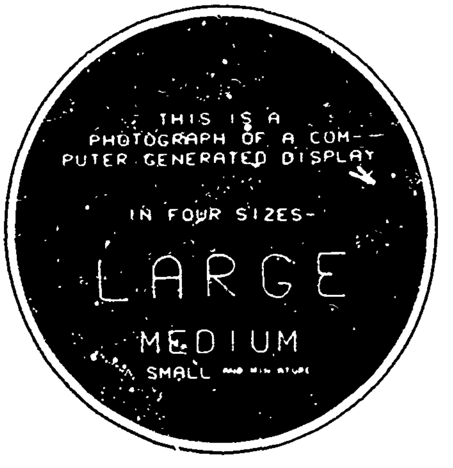


Fig. 3-17. Alphanumeric CRT display.

1.1.5 Printers

Printers are used to provide permanent records of alphabetic, numeric, or symbolic data furnished by computers, measuring devices, or other incremental data units. Printers that have a bank of symbolic or digital print hammers which move back and forth and are actuated by a single solenoid or other device are termed serial-entry printers. Printers in which each character in a print line or sheet is actuated individually by a separate input are termed parallel-entry printers. (Fig. 3-18)

1.1.5.1 Electric Typewriters

Electric typewriters are serial-entry electromechanical printers which use solenoid-actuated electric correspondence keyboards. Such devices generally use standard five-unit telegraph-coded inputs on punched tapes;

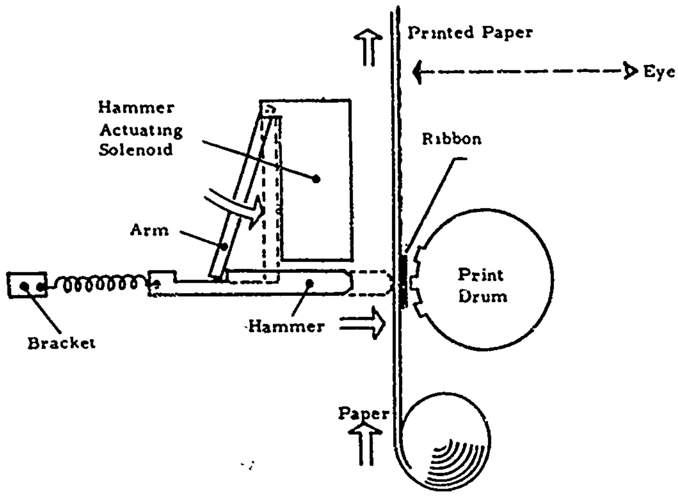


Fig. 3-18. Type-wheel printer.

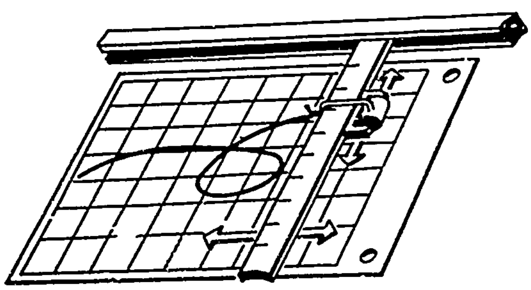


Fig. 3-19. X-Y recorder (plotter).

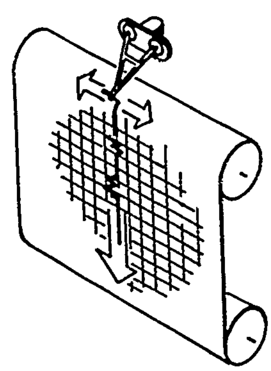


Fig. 3-20. Direct-writing galvanometer recorder.

some models have provision for the manual entry of information. Most typewriters of this kind operate at a maximum speed of 10 characters per second.

1.1.5.2 Type-Wheei Printers

Type-wheel printers are parallel-entry electromechanical devices which use a horizontally mounted drum on which are mounted a number of columns, each of which contains numbers and characters, and a programming wheel. As the drum is activated, each character for each column is presented to its associated solenoid-controlled hammer; an inked ribbon and paper move between the hammers and the type faces. Printing occurs when the solenoids actuate the hammers and press the paper and ribbon against the type faces. Such printing devices can operate at a speed of as many as 1,200 characters per second.

1.1.6 Recorders

Recorders are available with individual features which vary in regard to frequency response, range or span, accuracy, marking technique, etc. For example, circular charts might be used for batch or daily records, strip charts for monthly records, various miniature instruments when space is limited, X-Y recorders (plotters) for coordinate data, and recording oscillographs for high-frequency records. (Figs. 3-19, 3-20)

1.1.6.1 Direct-Writing Galvanometers

A direct-writing galvanometer is a recording device which uses a moving coil in a magnetic field to drive a stylus that imposes the image. Stylus techniques available include the use of an ink pen on the stylus tip, a heated stylus on heat-sensitive paper, and an electric stylus on electro-sensitive conductor-backed paper.

1.1.6.2 Plotters

Plotters, or X-Y recorders, are devices which permit the plotting of a given variable as a function of any other variable (e.g., latitude and longitude). Plotters reduce the time lapse between the occurrence of events and the graphic representation thereof and eliminate many of the errors inherent in manual data processing.

Electromechanical plotters are recording devices of the direct-writing, null-balance type which use a recording head driven by mechanical means. Proper chart or paper alignment is usually accomplished by the use of a mechanical or vacuum paper hold-down feature.

1.2 Auditory Displays

The types of auditory displays discussed in this section include the following:

a. Bells
b. Buzzers
c. Horns
d. Sirens
e. Recorded signals and directions

1.2.1 Bells

Bells are auditory displays in which clappers or plungers are used in combination with metallic bars, tubes, or cup-shaped gongs that vibrate and produce a physical sound. They may be activated by solenoids to produce a single chime or an extended ring. The sound output of bells used on naval vessels ranges from 75 to 87 db (based on a pressure reference level of 0.0002 dyne/sq. cm., measured at a distance of 10 feet from the signal source). The sound output of commercially available bells ranges from 72 to 91 db. Large-sized bells may have cup diameters up to 12 inches.

1.2.2 Buzzers

Buzzers are auditory displays in which vibrating armatures or plungers produce physical sound by striking metallic surfaces (e.g., the cover of the unit). Buzzers sound, characteristically, less musical than bells and have a relatively lower acoustical output (usually ranging from 62 to 70 db).

1.2.3 Horns

Horns are auditory displays in which mechanical means are used to produce sound by imparting motion to a diaphragm contained within a case that is fitted with a projector or grill. Horns may be electrically, manually or air driven and are generally used where an intense sound signal is required.

Horns in use in naval vessels have acoustical outputs ranging from 95 to 115 db in a frequency band of from 100 to 600 cps. Loud horns resonate at a frequency of between 250 and 350 cps.

1.2.4 Sirens

Sirens are auditory displays which are capable of producing a wailing up-and-down sound that is readily distinguishable from that of horns, bells, or other monotone auditory signals. The characteristic siren sound is produced by rotating one ported member, or rotor, within a similarly ported stationary member, or stator. The rotor combines functions of a rotary pump and a chopper; alternate stopping and releasing of the air flow produces the sound waves, the pitch of the signal rising or falling as the speed of rotation increases or decreases. (The maximum pitch attainable is a factor of the number of port openings and the maximum rpm.) Sirens currently used in naval installations have an acoustical output of approximately 105 db.

1.2.5 Recorded Signals and Directions

Audio playback devices are available for situations where audible signalling is required in the form of prerecorded warning or direction messages. For example, priority programmed verbal warnings are being developed for applications in which attention demands on the visual senses are already at a maximum and additional information is required, or, at the other extreme, where vigilance may be at a minimum as a result of long periods of monitoring infrequently occurring events.

2. Selection and Utilization

2.1 General

The selection and utilization of visual or auditory displays require consideration both of general factors that apply to all types of displays and of factors which are specific to an individual type of display component. This subsection discusses briefly the general factors involved; they include the following categories:

a. Requirements for information
b. Complexity of information
c. Compatibility between controls and displays
d. Constraints imposed by the work environment

2.1.1 Requirements for Information

The selection of any display is contingent on: (1) the information that the personnel must have for proper monitoring and operation of the particular system or equipment, and (2) the form in which this information should be presented. The following factors should be considered in determining what information is to be presented:

a. Utility: Is the information necessary for the decisions and responses which the operator must perform?

b. Redundancy: Is the same information available elsewhere on the panel (or in other locations), and, if so, is the redundancy considered desirable for purposes of reliability?

c. Relevancy: Is the information directly related to the tasks the operator must perform or is there superfluous information; i.e., is operational and maintenance information combined in a single indicator light and, if so, does it introduce any difficulties in interpretation?

d. Simplicity: Is the information presented in the simplest manner possible, or must the operator perform several steps to interpret its meaning; e.g., is the indicator light properly labeled and is the meaning of each particular color unambiguous?

The form in which the information is presented is dependent on the amount of information that must be observed by the operators and the speed and accuracy with which it must be processed. The form in which the information is presented may be related to the sensory or perceptual tasks required of the operators:

a. Qualitative reading: Where gross judgments must be made of the value or condition of some equipment function or status, and deviations from the normal or desired value or judgment must be noted: For example, "Off" or "On"; "In Tolerance" or "Out of Tolerance"; "Start," "In Process," "Complete"; "Normal" or "Alarm"; etc.

b. Quantitative reading: Where exact numerical values must be obtained. For example, "6.5 volts," "180 deg latitude," etc.

c. Check reading: Where scanning a display or group of displays is required to detect the existence of a normal or nonnormal value or condition. Displays for check reading may involve quantitative or qualitative information or both.

d. Observing change: Where a dynamic condition requires verification that the change is progressing at the normal or desired rate and in the normal or desired direction. Again, this can be presented in a qualitative or quantitative form.

The utilization of displays is seldom limited to one purpose. Therefore, it is important to determine first the primary function of the display and let this influence the selection (or design) most heavily. Then other, more secondary, uses of the display should be considered. For example, if a display is to be used for operations which are time-critical, and if a "go--no go" indication is adequate for monitoring and controlling the function, it would be undesirable to provide a more elaborate display. In addition, if a quantitative readout is required for maintenance purposes, it should not interfere with the rapid reading required under operational conditions. Or, if the two purposes cannot be successfully combined in a single display, then separate displays should be provided.

2.1.2 Complexity of Information

The sensory, perceptual, and processing capabilities of personnel should be considered in the selection and utilization of displays.[+] For example, the time available to read a display can affect the accuracy with which it is read. With unlimited time for reading (assuming sufficient training and adequacy of the display design), almost any display can be read to the limits of its accuracy. However, when both speed and accuracy are required, the selection and utilization (and design) of the display become more critical. In general, the simplest display that will provide the information and accuracy required should be used. Also, careful attention should be given to the placement, ambient lighting, and other factors related to its application.[++] Therefore, the following factors related to complexity of information should be considered:

a. How much decoding or encoding is required to interpret the display?

b. How much time is available for interpretation?

c. How many steps must be taken to interpret the display?

d. How many different displays must be interpreted before the operator is able to perform a control action?

e. How accurate and over what ranges must the display be read?

2.1.3 Compatibility Between Controls and Displays

Whenever displays are to be used in conjunction with controls, it is necessary to consider their compatibility in terms of their placement, labeling, physical appearance, direction-of-movement relationships, etc.[+++]

[+] Volume 1, Design of Systems, discusses these capabilities and limitations more fully.

[++] The subsection entitled Control and Display Panels and Consoles should be consulted for guidelines related to the placement of displays on panels

[+++] The subsection on Control and Display Panels and Consoles should be consulted for guidelines on placement, labeling, and direction-of-movement relationships.

In general, the greater the consistency (i.e., standardization) between controls and displays, the less the probability of error. However, standardization can be in terms of similarities or differences. For example, controls should always be physically distinguishable from displays, particularly where displays have control capabilities such as indicator light push-button switch combinations. Or, for direction-of-movement relationships, the direction of movement of the control should be consistent with the movement of elements of the display. For example, where rotary control switches are associated with adjustment of meters, movement of the control to the right should result in a movement of the meter pointer to the right, etc.

2.1.4 Constraints Imposed by the Work Environment

The working environment in which the displays will be used should be carefully studied to determine space restrictions, ambient lighting conditions, and noise conditions, to mention some of the important factors. These considerations are discussed in detail in subsequent paragraphs.

2.1.4.1 Illumination

The ability of personnel to interpret displays is dependent on the contrast between the displays, both lighted and unlighted, and the backgrounds against which they are viewed. Most of the FBM control and display panels and consoles are located in compartments with sufficient white ambient illumination to permit performance of most of the visual tasks associated with their operation. Some problems which exist in practice, however, should be noted. One of these is the problem of obtaining sufficient brightness with some of the colors used in indicator lights, particularly blue lights. Other problems are related to the use of low-level red light for both panel and ambient lighting in some of the compartments (Ship Control Area, and Sonar and Radar Rooms, etc.). These compartments require that the operators be dark adapted, which, in turn, imposes special display requirements and restrictions. For example, the size of the critical details in displays, such as the markings on meter scales, must be increased to compensate for the reduction in contrast. Also, color as a method of coding is not usable in these compartments.

2.1.4.2 Noise

The selection of auditory displays should be considered in relation to the expected ambient noise levels. For example, for verbal communications, the ambient level should not exceed 60 db in the 600- to 4800-cps bands. For monitoring of low-intensity signals, such as sonar, the noise level should not exceed 50 db, nor should the frequency of the ambient noise approach that of the signals being monitored.

2.1.4.3 Space

The amount of space available for displays on panels frequently presents problems. Compromises are often required in the amount of information that can be displayed and in the location of displays. Depth of components may also be a problem. Although only indirectly related to human factors considerations, available space may require the selection of components which are not the most desirable from the human factors standpoint.

2.2 Visual Displays

This subsection is concerned with the criteria for the selection and utilization of individual types of visual displays.

2.2.1 Indicator Lights

2.2.1.1 Requirements for Information

*[+] Indicator lights should be used for the display of qualitative information (i.e., one, two, or three conditions, excluding "Off") where check reading or other rapid responses are required of the operator. This includes indications of:

a. "On--"Off"

b. "In Tolerance--Out of Tolerance"

c. "Start--In Process--Complete"

[+] The * symbol indicates specific guidelines to be used in the selection and utilization of displays.

d. "Normal--Caution--Emergency," "Malfunction," "Radiation," etc.

e. "Standby--Ready"

f. "Command" where a specific response has been established for the operator, e.g., "Hold," "Fire," etc.

2.2.1.2 Conditions of Utilization

* Each indicator light should be confined to displaying information about a single function related to a specific equipment or component. Conversely, the operator should not be required to read more than one indicator to determine that function or status of the equipment or component.

* Indicator lights should be used to indicate (1) what function is being performed; (2) the status of the equipment; (3) what response should be made by the operator.

* Indicator lights should be used sparingly. Lights which are referred to infrequently (e.g., those used for maintenance) should not be placed in the central visual area of the panel or console.

* Normally, indicator lights should present a positive indication of status or process (e.g., power is off when "Power Off" light is on). There are exceptions, however, when:

a. Information is no longer required for the operation (e.g., after setup procedures have been completed or the missiles have been fired, etc.).

b. Alarm indications provided by indicator lights are accompanied by an auditory alarm, summary visual alarm, or other means of insuring that sufficient redundancy exists.

c. Modes of operation are displayed by separate indicator lights, e.g., "Test" mode versus "Operate" mode when handled by separate switch-light controls.

2.2.2 Digital and Word Readouts

This section is concerned with guidelines for the selection and utilization of small display devices which present alphanumeric information (i.e., numbers, letters, words, short phrases, or other symbols). These have been previously classified as random and sequential (continuous) access displays based on their mode of operation. Most of these devices which are available at the present time are limited in capacity to from 10 to 64 characters per unit. Multiple units can be placed side by side to increase the capacity.

2.2.2.1 Requirements for Information

* Digital or word readouts should be used when the direct readout of information is required.

The readout of information in a form which is suitable for immediate use by the operators has the advantage of reducing the amount of time required for interpretation and, as a result, may be expected to reduce the sources of error. For example, the use of a digital readout as opposed to a meter eliminates the sources of error associated with adjustment, interpolation between graduation marks, selection of scale (where multiple scales are involved), etc. Or, if a digital display provides readout in binary code which can be used directly for checkout, this again can be expected to minimize the amount of time required for interpretation and reduce the sources of error. Digital displays can be made to read as accurately as desired, provided adequate input signals are available.

* Digital readouts should be used when occasional (as opposed to continuous) readout of information is required (assuming the rate at which the information changes does not preclude the operator's being able to read the display).

The use of digital readouts is satisfactory for those situations where the operator must check the status of some condition or operation ("Missile Firing Order," "Test Number") but is not required to monitor the display continuously to determine direction of change or perhaps rate of change (e. g., change in heading, rate at which tube pressurization is occurring, etc.). Display of this type of information can be handled more effectively by scalar or pictorial displays.

For display of alphanumeric information which does vary rapidly and continuously (e. g., time displayed in seconds), the rate at which the change occurs should not exceed two characters per second. For example, if a counter is used to display values which change at a rate greater than two per second, the rapid movement of the counter drum will cause the display to become blurred.

* Sequential access digital readouts (i. e., counters and message belts) should be limited to the display of continuous variables (e. g., time, temperature, distance traveled, etc.), provided the rate at which the values change is not greater than two per second, as noted above.

The use of sequential access digital readouts for continuous variables is related to the problem of rapid indexing between selected characters. For display of noncontinuous information by means of counters and message belts, it is necessary to transverse all intermediate values; and, unless the device operates very rapidly and the display of intermediate values is blanked out, the display may be unsatisfactory.

* Random access digital or word readouts may be used for the display of either continuous (e. g., time) or discontinuous (e. g., test result) variables or other information (e. g., mode of operation).

2.2.2.2 <u>Conditions of Utilization</u>

When more than one unit must be used, side-by-side arrangement is recommended to provide a horizontal readout and thereby minimize difficulty in reading. Vertical arrays, such as have

been used for some binary and decade readouts, require more time to read due to incompatibility with normal eye scanning patterns and provide more sources of error.

* The number of significant digits displayed by sequential access displays (counters) should not suggest an accuracy which is greater than the inputs received by the device.

* Positions to the right of a decimal point which are not used should be blanked out or replaced with a stationary zero.

* Random access displays, particularly the projection and segmented matrix types, should be protected against "washout" due to high ambient illumination (i.e., loss of contrast between character and background) by use of a filter, hood, or other means which will preserve contrast.

Comparison of the individual types of digital and word readouts for the display of alphanumeric information is presented in Table 3-1.

2.2.3 Scalar Displays

2.2.3.1 Requirements for Information

* These displays should be used when quantitative readings over a continuous range of values are required and information about direction of change or rate of change is required (which would limit the usefulness of a digital readout).

* These displays should be used when check readings (qualitative judgments) of continuous variables and occasional quantitative readings are required.

Table 3-1

Utilization of Different Types of Digital and Word Readouts

	Random Information	Sequential Information	Single Letters	Single Digits	Limited Message	Detailed Message
Counters		X	X	X		
Segmented Matrices	X	X	X	X		
Gas Tubes+	X	X		X		
Edge-lighted+ Plates	X	X	X	X		
Projection Displays	X	X	X	X	X	
Back-lighted Belt Displays	X	X	X	X	X	
CRT Displays	X				X	X

+ These types of digital and word readouts generally are not as satisfactory as the others in terms of the ease with which they can be read due to display cross-talk and multi-plane presentation.

2.2.3.1.1 Moving-Pointer Fixed-Scale Displays

These displays are particularly useful for check reading where more than one scalar display is involved and the position of the pointers can be used as a reference point. For example, if a bank of pressure gages is involved and normally the values to be read remain within a relatively narrow range, it is possible to orient all of the pointers in the same direction and/or mark an area on the scale which indicates the normal area (i.e., a green band).

* These displays should be used for quantitative reading where relatively rapid pointer movement may be involved (moving scales or counters could be impossible to read under these conditions).

* These displays should be used where settings or adjustments are required which involve continuous variables (e. g., voltages).

* These displays may be used for some tracking applications, since they provide information about direction and rate of change.

2.2.3.1.2 Fixed-Pointer Moving-Scale Displays

* These displays should be used when precise quantitative readings are required.

* These displays can be used where direction or rate of change information is not important (a partially exposed scale may improve reading speed and accuracy when a large range of values is involved).

* These displays can be used for some setting and tracking tasks, provided the design compensates for certain direction-of-movement ambiguities. +

* These displays should be used when a range of values must be displayed in a limited panel space.

Moving-pointer displays require greater display surface and illumination on the panel than fixed pointer displays, since, for the latter, much of the scale can be placed behind the panel. Scale

+ Direction-of-movement relationships between controls and displays are discussed in detail in the section Direction-of-Movement Relationships, page 189 ff.

length on moving-pointer displays is limited unless multiple-pointer or pointer-counter combinations are used (the latter is to be preferred). Fixed-pointer scales reduce the distraction associated with large exposed display areas, and the scale can be made of virtually any length by the use of tapes.

2.2.3.2 Conditions of Utilization

2.2.3.2.1 Direction-of-Movement Relationships

* Scalar displays with circular scales and moving pointers should operate as follows:

  a. Clockwise movement of the pointer should increase the magnitude of the reading.

  b. Clockwise movement of the pointer should result from:

     (1) Clockwise movement of a knob or crank.

     (2) Movement forward, upward, or to the right of a lever.

     (3) Movement forward, upward, or to the right of a vehicle or controlled object.

  c. The pointer or marker should be at "twelve o'clock" for left-right directional information and at "nine o'clock" for up-down information.

* Scalar displays with vertical or horizontal straight scales and moving pointers should operate as follows:

  a. The pointer should move up or to the right to indicate increase in magnitude.

  b. Movement of the pointer up or to the right should result from:

(1) Clockwise movement of a knob or crank.

(2) Movement forward, upward, or to the right of a lever.

(3) Movement forward, upward, or to the right of a vehicle or controlled object.

* Scalar displays with circular moving scales produce certain ambiguities, particularly in relation to control movement. However, these can be minimized if the following practices are applied:

a. Counterclockwise movement of the scale should indicate an increase in magnitude.

b. If the associated control directly controls movement of a vehicle, the scale should move counterclockwise with:

(1) Clockwise movement of a knob or crank.

(2) Movement forward, upward, or to the right of a lever.

(3) Movement forward, upward, or to the right of the vehicle or controlled object.

c. Except when used for tracking displays, most of the dial should be covered, with the opening in the cover large enough to permit at least one numbered graduation mark to be visible at each side of any setting.

d. When used for tracking displays, the entire dial should be exposed.

Scalar displays with vertical or horizontal straight moving scales exhibit the same ambiguities as do the circular moving scale displays. However, these can be minimized by the following practices:

a. Numbers should increase from bottom to top or from left to right.

b. Scale should move down or to the left with:

(1) Clockwise movement of a knob or crank.

(2) Movement forward, upward, or to the right of a lever.

(3) Movement forward, upward, or to the right of the vehicle or controlled object.

2.2.4 Cathode Ray Tube Displays

2.2.4.1 Requirements for Information

* CRT displays should be used when there are requirements for:

a. Direct representations of electrical parameters (e. g., waveform outputs of test equipment or analog computers, etc.).

b. Presentation of large arrays of alphanumeric information.

c. Representations of objects in space (e. g., television, radar, and sonar and abstract pictorial displays) where detection, identification, or tracking may be required.

The use of CRT displays is effective for the presentation of information that permits man to use his capabilities of discrimination and identification of patterns and spatial relationships under high noise

levels or where large amounts of information must be integrated to determine appropriate control responses. The use of CRT displays still remains the most effective means of presenting tracking information, although solid-state techniques (such as electroluminescence) may be usable in the future.

2.2.4.2 Conditions of Utilization

2.2.4.2.1 Illumination

The ambient illumination under which CRT displays are used has considerable effect on the operator's ability to read or detect signals. When the ambient illumination exceeds the brightness of the scope face, visibility may be reduced by:

a. Specular reflections (bright glare spots) from the glass surface of the scope face.

b. Excitation of the phosphor in the tube reducing the signal-to-background contrast.

c. Loss of sensitivity of the eye resulting from incomplete adaptation.

Visibility is optimum when the operator is adapted to the level of scope brightness. Some loss of dark adaptation can be tolerated when the operator must perform other accurate visual tasks which require that the ambient lighting be somewhat brighter than the average scope brightness. Both absolute darkness and illumination greater than 5 ft L higher than screen brightness are unfavorable for proper visibility of scope targets.[6]

* The operator should not be exposed to ambient illumination greater than 100 times the average brightness of the scope.

* When used in low-level (red) lighted areas, the illumination on the scope face should be maintained at as low a level as possible. However, it must be sufficiently high to permit photopic vision. (The threshold of photopic vision is approximately 0.01 ft L.)

2.2.4.2.2 Arrangement

* Cathode ray tube displays should be so arranged, wherever possible, that the scope face is perpendicular to the operator's normal line of sight. (See Fig. 3-45, page 165.)

2.2.5 Printers

2.2.5.1 Requirements for Information

* Printers should be used when a permanent record of numeric, alphabetic, or other symbolic information is required and rapid readout of the information is not required.

The selection of printers on bases other than requirements for permanent record of information have to do primarily with the capacity of the devices. These include:

a. Rate of printout: Print rates are stated in terms of "lines per minute" or "characters per second." Generally, the print rate will be selected on the basis of the amount of information which must be printed rather than the readout requirements of the operator.

b. Capacity of printout: Printout capacities are stated in terms of "digits per line" or "number of columns." Printers should be selected which provide the minimum number of columns or digits per line, since increasing them reduces the readability of the record.

c. Alphabet or vocabulary size: Standard printers, such as teletypewriters, generally utilize 63-symbol vocabularies. Numerical or digital printers utilize standard decimal symbols with additional symbols indicating values, relationships, or punctuation. The nature of the information to be printed will determine the selection of the vocabulary.

d. Roll capacity: Printers should be selected which will provide sufficient paper storage capacity to avoid frequent reloading. Printout requirements (size of printing, line, and column space) will determine minimum roll capacity.

e. Size of unit: Available space and configuration of the printer will influence selection. Special environment within the submarines may require shock-mounting and drip-proofing.

f. Maintenance: Submarine enclosures in most cases dictate front access for maintenance and, therefore, require the selection of specific printer packaging techniques.

2.2.5.2 Conditions of Utilization

2.2.5.2.1 Illumination

* Supplementary lighting (e.g., flood lighting) or some method of integral lighting (e.g., edge-lighting, wedge-lighting) should be provided to illuminate the printout.

Supplementary lighting is desirable for printers used on board the submarines since it is not practical to provide sufficiently high levels of ambient illumination to accommodate an accurate visual task such as continuous monitoring of a printed record. For reading periods of one hour or more, it is desirable to maintain the level of illumination for 10 to 20 ft C or greater on the printed record. Less illumination, such as that provided in the low-level (red) lighted compartments on the submarine, would require large bold type (i.e., a minimum of 1/8-in. character height and 1:5 strokewidth-height ratio).

* Use of transparent covers or viewing windows to protect the printer readout, together with any supplementary lighting, should not result in glare or specular reflections which interfere with the readability of the printout.

The mounting of the supplementary lighting below the viewing window will usually eliminate this problem.

2.2.5.2.2 Noise

* Noise level due to operation of the printer should be minimized (i.e., held below 50 db) by adequate sound baffles within the unit.

2.2.6 Recorders

2.2.6.1 Requirements for Information

* Recorders should be used when there are requirements for permanent records of variables which vary as a function of time (e.g., drift about the output axes of gyros).

* Plotters (i.e., X-Y recorders) should be used when one variable must be plotted as a function of any other variable (e.g., latitude versus longitude). (These variables may also be plotted as a function of time.)

The selection of recorders on bases other than those cited includes:

a. Channel capacity: Capacity should be sufficient to permit recording of all information without overlapping of data. If overlap is necessary, traces should be identified by coding (color, symbol, modulation, etc.).

b. Frequency response: Inputs to recorders may be discrete or continuous. For discrete events occurring at frequencies of less than 2 per second, null balance or chopper-bar recorders may be used. Direct-writing galvanometer recorders are available with frequency responses of from 30 to 100 cps, with special devices from 150 up to 800 cps. Light-beam techniques can provide frequencies up to 10,000 cps.

c. Rectilinear vs. curvilinear coordinates: Whenever possible, a recorder using rectilinear coordinate traces should be used, since they are much easier to interpret and less subject to error than is a curvilinear record.

d. Marking techniques:

(1) Ink stylus recorders have the following advantages: a wide range of recording speeds without stylus readjustment; low stylus friction; and use of economical paper and records that can be reproduced by most of the common copying processes. Ink recorders have the disadvantages of spattering of ink at high frequencies, spillage of ink under severe vibration, and drying of the ink in an idle pen. They also generate a curvilinear trace unless special linkages are used.

(2) Electric arc stylus recorders avoid ink splatter or spillage, but may generate curvilinear traces and usually produce fumes during operation. The recording current must usually be changed when paper speed or input frequency changes. The friction of the electric stylus is greater than that of the ink or hot stylus. Recording mechanisms are relatively expensive, and reproduction of the trace involves a photographic process.

(3) A hot stylus may be used for recording signals of less than 120 cps. A well-defined line can be traced. Stylus temperature must be readjusted with changes in signal frequency and paper speed. Units using a heated stylus are usually high in cost, and reproduction of the tracing may require photographic processing, depending on the exact type of paper used.

The factors to be considered in selecting plotters include:

a. Scale range and paper size: The plotter should provide sufficient scale range for each variable. Paper size and scale range should present a display which is immediately readable and interpretable. Standard paper sizes of 8-1/2 by 11 inches, 11 by 16-1/2 inches and 30 by 30 inches are most commonly used. Strip-chart rolls are also available. Sensitivities from 0.5 mv/in. to 50 v/in. in roughly 2:1 steps are available.

b. Slewing speeds: Slewing speeds should be provided which permit rapid and accurate positioning and/or calibration of the plotter marking device. Slewing speeds vary from 10 to 40 in/sec. Higher speeds allow higher point-plotting rates and better dynamic performance. Usable rates are roughly one-half the slewing speed, depending primarily on the writing technique (e.g., ink-feed system, etc.).

c. Frequency response: Except for special cases where high frequency response is required, electromechanical rather than optical plotters should be selected for shipboard application because ruggedized equipment and a large (i.e., up to 30 x 30 in. or larger) recording area are usually required.

d. Accuracy: The accuracy of the plotter should be commensurate with the inherent accuracy of the system. Electromechanical plotters can be designed to provide accuracy to up to 0.50% for a 30 by 30 inch plotting area. High accuracy is expensive and wasteful if not required.

2.2.6.2 Conditions of Utilization

2.2.6.2.1 Illumination

* Supplementary lighting (flood lighting) or some form of integral lighting (wedge-lighting, etc.) should be provided for the recording surface.

* Recorders used in low-level(red) lighted areas should have adjustable brightness levels between 0.5 and 1.5 ft L, and the lighting should be evenly distributed over the entire recording surface.

* Use of transparent covers or viewing windows over the recording surface, together with any supplementary lighting, should not produce any glare spots or reflections.

The mounting of supplementary lighting under the cover will usually eliminate this problem.

2.2.6.2.2 Mounting

* Recording surfaces should be mounted as close to perpendicular to the line of sight as possible when viewed from the operator's normal position. (See Fig. 3-45, page 165.)

* When writing on the recording surface is required, the surface should be sloped 45 deg or less from the horizontal; convenient access to the surface should also be provided.

2.3 Auditory Displays

This subsection provides guidelines for the selection and utilization of auditory displays as a group (i.e., bells, buzzers, horns, sirens, and recorded signals and directions).[+] Differences in selection or utilization criteria among the different types of auditory displays are indicated.

[+] Since interior communication equipment depends on the auditory sensory modality, it could be classified under auditory displays and discussed here. However, because of its unique differences from the more abstract auditory signals discussed here, it is treated in a separate subsection entitled Design of Interior Communication Equipment.

?.3.1 Requirements for Information

* Specific conditions for which audible signal displays should be used include the following:

  a. General alarms (e.g., "Collision," "Missile General Quarters"): Sirens may be applied for this purpose, although horns or bells are more commonly used aboard ship and can be just as effective if their output is sufficiently higher than the ambient noise level to insure that they will always be heard.

  b. Commands and directions: Bells or buzzers may be used, to a limited extent, to provide specific commands or directions (e.g., "Start" or "Stop" orders, paging, etc.) or recorded signals and directions may be used to impart more detailed information and directions. (These are probably most effective for monitoring the condition of equipment and taking corrective actions as directed.)

  c. Specific alarms or danger signals (e.g., "Over Radiation," high temperature, etc.): Any of the audible signals can be used for this purpose, although (as noted in the following sections) the number of such signals should be limited, and each should be distinctive in sound.

Auditory signals have been used most frequently for alarms and warnings because of their unique ability to command immediate attention. Some of the advantages of auditory alarms are that they can be employed to supplement (or, in some instances, substitute for) visual displays where extremely heavy (or light) workloads exist, or where the operator may not always be located at his station and may fail to notice a visual display. Some of the disadvantages of auditory signals are that they are limited in the amount of information they can impart and that, if they are not sufficiently intense, they can very easily be masked by ambient noise.

* Auditory displays should be used (usually to supplement visual displays) when:

a. Operators may not always be located at a console (such as under prolonged watch conditions), and critical conditions must be continuously monitored (e.g., monitoring of the missile tube environment).

b. Environmental conditions handicap visual presentation of information and cannot be compensated for by proper lighting.

c. Visual monitoring tasks are excessive because of the amount of information that has to be processed within the time available.

d. Rapid response is critical (e.g., response to "Over Radiation' or "Missile Jettison" alarm).

e. Alarms could be expected to occur at any time (e.g., occurrence of equipment malfunction alarms for continuously monitored functions, "Missile General Quarters").

f. Many alarm circuits are monitored and it is desirable to provide a summary alarm for initial attraction of attention (e.g., the auditory alarm associated with the integrated Monitor Panel in the SSB(N) 616 class).

* If a large number of events must be designated by auditory signals, or the response to an auditory signal must be complex, a recorded verbal message can be used either solely or immediately following an attention-getting warning. Speech has an inherent advantage in that little or no training is required for its recognition. To prevent confusion, the verbal message must be unequivocal and must be repeated enough times to insure that the message is understood.

2.3.2 Conditions of Utilization

* Auditory displays should, in general, be supplemented by visual displays.

Auditory displays impart a limited amount of information, and the operator may need to refer to other sources of information to determine appropriate responses.

* Auditory signals must have sufficient intensity or different tonal qualities to be heard in all locations and under all expected levels of ambient noise.

* The number of pitches or intensities should be limited to five increments.

* Alarms of the highest attention-getting quality (e.g., the loudest and most annoying) should be used for warnings of the highest priority.

* Alarms that have long been associated with a specific warning should be maintained (e.g., a fire bell).

* Auditory signals must be distinctive and not confused with any others that may be used in the same compartment.

* Auditory signals should be of short duration (i.e., 5 to 10 sec). (If there is concern that the signal may not be responded to, it should be repeated at regular intervals.)

* Several small auditory devices properly distributed about a compartment should be used, rather than a single, large output device.

In large unpartitioned areas, the major disadvantage of the single large device is that it may deafen the man near it and may not be heard by the man some distance from it, particularly under conditions of high ambient noise level. Small partitioned areas usually require low-decibel signal devices. The use of smaller devices properly located has the advantage of compensating to some extent for high ambient noise levels.

* Small buzzers or bells may be used as local alarm indicators for individual equipments.

3. Design

3.1 General

The effectiveness of the design of visual displays is dependent on the extent to which the operator is able to detect an object within a background (e.g., a target on a radar scope) and to resolve the critical details of the object (e.g., to read a legend on an indicator light) so that it can be identified. Both detection and resolution, particularly the latter capability, are dependent upon the size of the critical details within the display, the contrast between details and background, the illumination level of the display, and the amount of time available for observation. Within limits, the reduction of any one of these can be compensated for by an increase in one or more of the others. These factors are discussed individually below.

3.1.1 Visibility of Displays

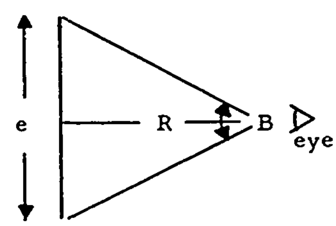
3.1.1.1 Dimensions of Critical Detail

Persons having visual acuity acceptable to the Navy (Snellen rating of 20/40) can resolve details down to approximately 2 minutes of visual angle under ideal conditions of illumination and contrast--if sufficient observation time is provided. However, since visual displays are seldom viewed under optimum conditions, it is preferable to base the dimensions of critical details on a visual angle of 2.5 minutes in order to provide an adequate safety margin.+

When dimensions of critical details have not been specified, they may be derived by use of the following formula:

$$\tan\frac{B}{2} = \frac{e}{2R}$$

$$\frac{\text{Tan } B}{2} = \frac{-e}{R}$$



(1)

+ Marking criteria specified in this handbook are based on this criterion. For further reading in visual perception, see Stevens(76)

where B = the visual angle,

e = the size relating to some aspect of the stimulus (e.g., length of line, a diameter, a separation between points), and

R = the distance between e and B along the line of regard.

Where B is small (i.e., tan B = B, approximately),

$$B = \frac{e}{R} \text{ in rad.} \tag{2}$$

or

$$B = \frac{57.3e}{R} \text{ in deg.} \tag{3}$$

Equations (2) and (3) represent an overestimation of B by 1 per cent at a value of 10 degrees and by 3 per cent at 17 degrees. When e is curved and all points are equidistant from the eye's reference point, Equations (2) and (3) are exact.

3.1.1.2 Contrast of Critical Detail

The amount of contrast necessary to detect critical detail in a background 99 per cent of the time is shown in Figure 3-21 for various visual angles and degrees of brightness. The contrast curves from 0 to 100 per cent apply to backgrounds that are both brighter and darker than the details involved. The curves shown for contrast greater than 100 per cent apply only to details that are brighter than their background. Data on which Figure 3-21 is based reflect capabilities of a fully adapted human eye when used by a highly trained observer under constant levels of background illumination.

There is no known lower limit of visual angle for bright objects appearing against a dark background. Moreover, the visual angle subtended by visible lines and squares against bright backgrounds may be much smaller than those shown in experimental data graphs, if the background brightness is greater than that of the detail involved and if there is high contrast. Hence objects or critical detail in a display having a high contrast ratio require a lower level of brightness for perception than objects having a low contrast with their backgrounds.

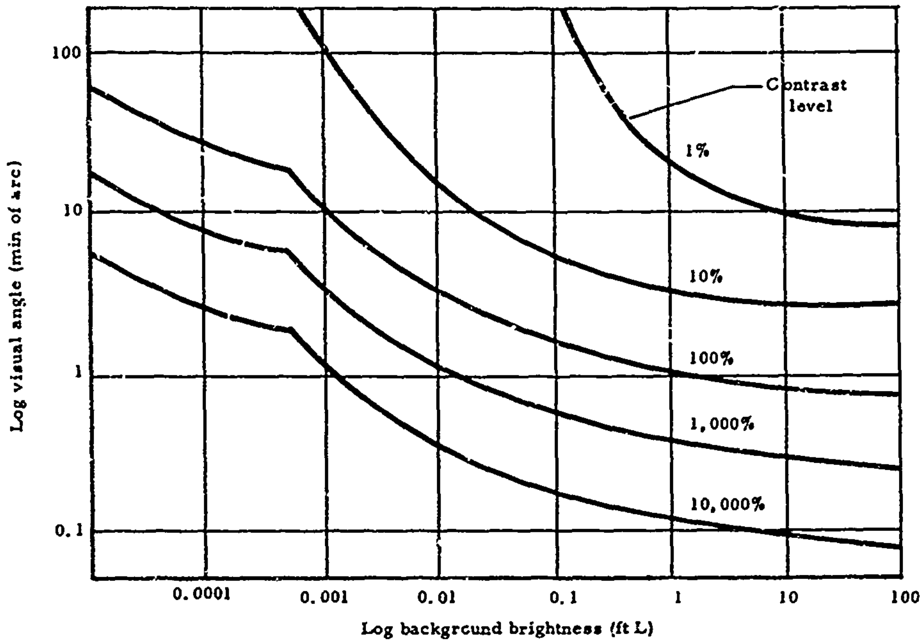


Fig. 3-21. Contrast required for 99% probability of detection. (4)

The actual contrast ratio can be derived by use of the following formula:

$$C = \frac{B_b - B_o}{B_b} \times 100 \quad \text{(test objects darker than background)}$$

$$C = \frac{B_o - B_b}{B_b} \times 100 \quad \text{(test objects brighter than background)}$$

where C = the contrast ratio (in %)

B_o = the brightness of the test object, and

B_b = the brightness of the background.

3.1.1.3 Illumination

When discussing amount of illumination, two terms are generally used: the footcandle and the footlambert. The footcandle refers to the amount of illumination that falls on a particular area or object; this measurement of light energy is directly obtained with the use of a standard footcandle meter (the photocell should be equipped with an eye compensating filter). The footlambert is an expression of the amount of light reaching the eye of the observer, this is the brightness of the object, and it is generally a product of several primary and secondary reflections. If it were possible to project one footcandle of light on a perfectly diffuse surface, then that surface would have a brightness of 1 footlambert (ftL). However, the theoretical "perfectly diffuse" surface does not exist. The brightness of objects will vary even if the footcandle value is held constant. Hence, if recommendations for quantity of illumination on the object are given in footcandles, then the percentage of reflectance of the object must be included to determine actual brightness of that object. Conversely, if recommendations are given in terms of footlamberts, this value must be divided by the reflectance in order to determine the footcandle equivalent.

General recommendations for individual display components, as well as over-all panel and console lighting are consolidated in Table 3-2.

Table 3-2

Display Lighting(4)

Condition of Use	Recommended Lighting Technique	Brightness Markings	Brightness Adjustments
Instrument lighting, dark adaptation critical.	Red or low color temp, white internal lighting. Type III in MIL-P-7788A, or wedge-lighting	0.02 to 0.1 ftL	Continuous thru range
Instrument lighting, dark adaptation not critical.	Same as above.	0.02 to 1.0 ftL	Continous thru range
Instrument and console lighting, no dark adaptation required.	Supplementary or internal white flood as required	1 to 20 ftL	May be fixed
Possible exposure to bright flashes	Supplementary white flood	10 to 20 ftL	Fixed
Chart reading, dark adaptation required	Supplementary flood, operator's choice of red or white	0.1 to 1.0 ftL on white portions of chart	Continous thru range
Chart reading, no dark adaptation required	Supplementary white flood	5 ftL or above	May be fixed

Table 3-3 presents a comparison of five general levels of visual task difficulty and of the amount of contrast and brightness required.

Table 3-3

Contrast and Brightness Required for Visual Tasks[46]

Category of Visual Task	Contrast Range[†]	Required Brightness in Footlamberts
Most difficult	0.55 and below	420 and up
Very difficult	0.56 - 0.60	120 - 420
Difficult	0.61 - 0.70	42 - 120
Ordinary	0.71 - 0.80	18 - 42
Easy	0.81 and above to ∞	up to 18

[†] For test objects which are brighter than background, contrast ranges from C = 0 to C = ∞ ; darker than background, contrast ranges from C = 0 to C = 1.

3.1.1.4 Flicker

Flicker, which is a sensory effect produced when flashes of light are repeated slowly, is a problem in several types of displays. (For example, digital and word readouts have been developed on the stroboscopic principle, and CRT type character generators electronically retrace symbols many times per second.) At very low flash rates, the alternations of light and dark produce a feeling of ocular tension, as if the eye muscles were trying to contract and relax concurrent with the flashes. Such ocular discomfort is greatest just before the dark phase of the cycle emerges as a definite shadow.

The rate of flashing at which the impression of steady illumination is obtained is known as the critical flicker frequency (CFF). Experimental data show that factors involved in the determination of the flash rate include the following:

a. The intensity of illumination, both of the flash and of the field in which the flash appears (average background brightness).

b. The area of the object which is flashing.

c. The ratio between the durations of the light and dark periods of the cycle.

3.1.1.4.1 Intensity

The CFF is proportional to the logarithm of the illumination intensity. When the intensity is very low (near absolute threshold of vision at approximately - 6 log millilamberts), flashes as infrequent as 3 or 4 per second will give the impression of continuous illumination. When intensity is high (above 100 millilamberts), the highest flash rate that can be distinguished by the human eye is approximately 50 to 55 cps.

3.1.1.4.2 Area

The CFF value increases as the area of the test object grows larger.

3.1.1.4.3 Light-Dark Ratio

The value of the flash rate changes as the light-dark ratio varies. In general, as the light-dark ratio increases ($\rightarrow 1.0$), the CFF tends to decrease.

3.1.2 Coding

Coding may be used to emphasize the information provided by the display and to permit a simple and immediate assessment of condition without the necessity for reading and evaluating individual indications. Table 3-4 provides a comparison of techniques for coding.

Table 3-4

Summary Comparison of Techniques for Coding

Code Dimension	Maximum Number of Code Steps	Evaluation	Comments
Color	11	Good	Objects of a given color easily and quickly identified in a field of various colored objects.
Numeral and Letter	(Unlimited)	Good	Number of coding steps unlimited. Little space if there is good contrast and resolution.
Shape	15 (or more)	Good	Certain geometric shapes are easily recognized. Figure should represent symbolically the action recorded by the display.
Size	4	Fair	Difficult to make judgments about the relative sizes of two or more display targets.
Brightness	3-4	Poor	Limited number of usable code steps. Most effective use is with two-step code. Difficult to attain discriminable differences in practice.
Location	(Unknown)	Fair	Particularly important in complex layouts.
Flash	1	Good	Limited to either flashing or steady state. Most effective for attention-getting or warning purposes.
Flash Rate	5	Poor	Distracting and fatiguing. Interacts poorly with other codes. Requires high ambient illumination if high (50 cps +) flash rates are used.
Line Length	4-5	Poor	Limited number of usable code steps. Subject to optical illusion.
Angular Orientation	4	Poor	Limited number of steps. Difficult for absolute judgments (i.e., noncomparative).
Stereoscopic Depth	(Unknown)	Poor	Requires complex 3-D electronic displays. Effective for presenting general relationships (i.e., qualitative task), but usually detrimental to quantitative tasks such as readout of range and altitude.
Pattern and Configuration	4-5	Poor	Limited number of code steps. Usually confusing unless used in combination with color, etc.
Auditory	5	Fair	Used for attention-getting purposes.

3.1.2.1 Techniques for Coding

3.1.2.1.1 Color Coding

For practical purposes, ten different hues of color and white can be identified with minimum training by the normal (i.e., noncolorblind) observer. A discriminable brightness of at least 1 millilambert is required, and a visual angle of 45 minutes of arc must be subtended; however, brightness or size could probably be reduced by a factor of 10 without seriously affecting the identification accuracy.

In general, the ten spectral hues acceptable for color coding are the following (in addition to black and white):

Wavelength (in Angstroms)	Color
4300	Violet
4760	Blue
4940	
5040	
5150	Green
5360	
5820	Yellow
5960	
6100	
6420	Red

For SP-furnished equipment, five colors will be used as specified in Table 3-6, Section 3.2.1.3, page 62.

3.1.2.1.2 Numeral and Letter Coding

Numerals and letters (e.g., labels) are particularly useful for coding purposes since the number of different codes that can be devised is unlimited. A single figure or a combination of figures may be utilized effectively for coding purposes if requirements of contrast, illumination, and size are fulfilled.

3.1.2.1.3 Shape Coding

Experimental evidence has shown that there are at least fifteen distinguishably different geometrical figures which may be used for coding purposes in the design of displays (e.g., cross, triangle, circle,

square, rectangle, diamond, ellipse, etc.). The figure selected for use in a particular display should bear some pictorial relationship to the information being displayed if at all possible. When used with color coding, shape coding is an effective means of combining two dimensions of information in a single display.

3.1.2.1.4 Size Coding

Both relative and absolute types of size coding may be used to a limited extent. In relative size cod the operator must be able to make judgments about the relative sizes of two or more display targets; hence, relative size coding is not practical for critical operations where there is little time for comparison of viewed objects. In absolute size coding, no opportunity is provided for comparison of objects; hence, any differences between items viewed must be larger than those applicable to the use of relative size coding. However, size coding on an absolute basis must be restricted to no more than four steps in order that the size of displays will not exceed practical bounds.

3.1.2.1.5 Brightness Coding

The number of stages of brightness that an observer can identify correctly depends in part upon the range of brightnesses available; but, even when a wide range of brightnesses is available, only three or four levels of brightness can be readily identified. In general, brightness coding is unsatisfactory because the contrast between bright and dim signals tends to obscure the dim ones. Moreover, extensive periods of viewing uneven levels of brightness can induce fatigue. Hence, brightness coding is most effective when limited to two steps (e.g., dim and bright).

3.1.2.1.6 Location Coding

Location, or position, coding provides for the spacing or positioning of displays (and controls) in groups so that they are distinguishable from each other. Location coding can be important to complex layouts, since it can be accomplished in a number of ways, such as by adequate spacing of display or control groups (horizontal separations are preferable to vertical separations), by outlines around each unique group of displays, by color coding of different locations, by symmetry, and by placement on different planes with respect to the operator.

3.1.2.1.7 Flash Coding

Flash coding may be used as an attention-getting device when an important warning is to be indicated. Such coding is most appropriately used with either an illuminated colored indicator or with an auditory display. When combined with a visual display, the flasher should have a provision whereby the operator can stop its action and return the indicator to a steady indication, since flashing signals may interfere with observation of the basic display.

Flash-rate coding is, in general, unsatisfactory because high levels of brightness are required if high flicker rates are to be identified. The task of selecting signals being communicated by particular rates of flicker from among those in a field of flickering signals is difficult; moreover, available data indicate that no more than five identifiable flash rates should be used, even under optimum conditions.

3.1.2.1.8 Line Length Coding

Line length coding may be used in pictorial displays to represent prevailing conditions in a continuous fashion or in nonpictorial displays to represent discrete steps (e.g., bar chart displays). However, it is difficult to distinguish among more than a few steps if the lines are randomly scattered over the display, and the appearance of line length is greatly affected by the amount of area which surrounds it.

3.1.2.1.9 Angular Orientation Coding

Angular orientation coding is best considered in relation to a bank of identical indicators wherein the direction of the pointers for normal operation has been standardized and deviation of any pointer from that direction is an indication of an abnormal condition. Angular orientation coding may also be used to code the position of a single pointer in reference to the horizontal. However, probably no more than four steps could be used without the introduction of the possibility of observation error.

3.1.2.1.10 Stereoscopic Depth Coding

Stereoscopic depth coding can be used to give a realistic dimension to certain display information, such as range or depth.

However, only a few steps can be used, and this type of coding is not as effective as two-dimensional displays for obtaining exact or quantitative readings.

3.1.2.1.11 Pattern and Configuration Coding

Patterns such as cross-hatching, horizontal lines, vertical lines, diagonal lines, etc., may be used for coding. However, the limited number of patterns that can be used may contribute to operator confusion when displays are to be viewed under nonoptimum conditions. Pattern coding based on the configuration presented by a number of identical displays may also be used. When applied, for example, to an indicator light having multiple lamps, light barriers can be used to form a split-cap indicator whereby only selected portions of the display are illuminated as representations of specific bits of information concerning the signal.

3.1.2.1.12 Auditory Coding

Auditory coding is usually used to supplement visual display information in cases of warning. In addition, auditory coding may be used as an attention-getting device to alert the operator to a need for monitoring his visual displays.

3.1.2.2 Combinations of Coding

The simultaneous use of more than one type of coding can provide a means for more efficient and effective use of displays. Multiple coding presents a means by which a redundancy of coded information may be provided to insure receipt of the required indication and allows more than one dimension of information to be presented in a single display. Multiple coding should also be used to differentiate between controls and displays where there is similarity of appearance (e.g., between simple indicator lights and similar push-button switch-light units by providing a shape-coded or oval mask on all push-button switch lights). Table 3-5 outlines various combinations of coding techniques that are effective for use in displays.

3.1.2.3 Compatibility of Coding

Coding methods can be considered to be quantitative, qualitative, or both in the same manner that information is classified.

Table 3-5

Summary of Effective Combinations of Coding Techniques

	Color	Numeral and Letter	Shape	Size	Brightness	Location	Flash	Flash Rate	Line Length	Angular Orientation	Stereoscopic Depth	Pattern and Configuration	Auditory
Color	-	X	X	X	X	X	X	X	X	X	X	X	X
Numeral and Letter	X	-		X		X	X						
Shape	X		-	X	X		X	X				X	
Size	X	X	X	-	X		X					X	
Brightness	X		X	X	-								
Location	X	X				-				X			X
Flash	X	X	X	X			-					X	X
Flash Rate	X		X					-					
Line Length	X								-	X			
Angular Orientation	X					X			X	-			
Stereoscopic Depth	X										-		
Pattern and Configuration	X		X	X			X					-	
Auditory	X					X	X						-

Codes which rely on geometric shapes or colors are considered to be qualitative codes because the various colors and shapes are different qualitatively. Codes which rely on size, brightness, line length, etc., are considered to be quantitative codes because the differences are quantitative. Number codes can be considered to be either qualitative or quantitative. For ease of interpretation, qualitative codes should be used to code qualitative information, and quantitative codes should be used to code quantitative information.

When a symbol is used, common associations such as the following should be considered:[12] (See Fig. 3-28, page 82.)

a. An arrow points in the direction of travel

b. Size or number indicates magnitude

c. Red indicates danger or emergency

d. A flashing signal indicates an emergency

e. Location is at the geometric center of the symbol or at a dot.

Misuse of multiple coding schemes can result in unnecessary complexity of interpretation. Table 3-5 should be used to select those coding combinations which are most effective. In general, the number of coding techniques selected should equal the dimensions of information which are presented. For example, if two dimensions of information are required (hostile versus friendly and ship versus aircraft), two dimensions of coding (e.g., color and shape) are appropriate.

3.1.3 Reliability

The reliability of a display is concerned with the requirement that the information be clearly and reliably presented to the operator. The display component and all associated circuitry should be so designed that failure rate is minimized, information intelligibility is maximized, and a positive indication of operation is provided to insure that partial or complete display failure will not go undetected. Hence, reliability is concerned with both the design of the display component and the nature of the information presented by it.

3.1.3.1 Equipment

Reliability of operation requires that the display present the information whenever desired. Where correct presentation cannot be guaranteed by a single information circuit, reliability can often be improved by providing external references against which display operation can be compared and/or calibrated (e.g., the use of external test equipment for meter calibration).

3.1.3.2 Information

Reliability of information pertains to intelligibility. Hence, in addition to insuring that the information appears on the display, it is necessary to minimize any possibility that the operator might receive the information incorrectly (i.e., fail to detect it at all or interpret it incorrectly). Ambiguity of representation because of improper or inadequate display design or use should be avoided. A further consideration pertaining to information reliability requires that each display be designed in such a manner that the operator is aware that the display is or is not functioning properly (e.g., shadowing effect on the display screen of an indicator light when one of two lamps operating in parallel burns out), or, in special cases, is temporarily disabled. The display design should preclude an operator from making incorrect assumptions, responding to noncurrent information, or otherwise failing to initiate appropriate responses because of the inadequacy of the information. However, absolute positive indication of operation is not always possible because necessary instrumentation may not be compatible with other design requirements.

3.1.4 Maintainability

Although the general maintenance philosophy for the FBM system is one of replacement only, some shipboard repair will always be necessary. Hence, both repair and replacement must be considered in display design.+

+ The section Design of Equipment for Maintenance provides detailed guidelines for maintenance requirements.

3.2 Visual Displays

3.2.1 Indicator Lights

3.2.1.1 Dimensions

The specification of dimensions for indicator lights is dependent upon such considerations as the following:

a. Whether or not the indicator is to have a legend inscribed on the display screen, and, if so, the dimensions of the area required.

b. Whether or not size coding is to be used to differentiate between critical and noncritical displays.

c. Expected viewing distances and angles.

d. Panel space constraints.

e. Number of lamps to be used.

f. Standardization of control and display inputs (e.g., the components which have been developed as part of the Mark 84 Fire Control Subsystem).

*[+] Indicator lights to be used in the FBM system should approximate the following dimensions:[++]

a. Miniature light units (e.g., pilot lights) should have a maximum outside diameter of approximately 1/2 in.

[+] The * symbol indicates specific guidelines to be used in the design of displays.

[++] These dimensions are based primarily on visual considerations (i.e., sufficient brightness and/or space for legends); however, components are available which closely match these dimensions. (See illustrations of single- and multi-status indicator lights, page 5.)

b. Single-status indicator lights (i.e., single color) should have panel dimensions of approximately 1-1/4 in. by 5/16 or 1/2 in., depending upon the size of the legend(s) to be used.

c. Multiple-status indicator lights (i.e., multiple color) should have panel dimensions of approximately 1.2 by 1.2 in.

d. Over-all depth of all indicator light units should not exceed 2 in. For combined displays (e.g., switch-display components), the depth dimensions should not exceed 4 in.

3.2.1.2 Illumination

Indicator lights should operate with sufficient brightness to insure that their operation and color can be detected under all expected conditions of ambient illumination.

* Brightness of the display screens of all activated indicator lights should be at least three (and up to five) times the brightness of the unlighted screen and the panel surface or the area which is to surround the indicator light.

* Provision should be made for the control of indicator light brightness when the range of ambient illumination is subject to variation; this requirement is particularly important for applications where dark adaptation is to be required.

* Light output of miniature lamps used in indicator lights should be balanced by sorting to within ±25% of rated output.

* Brightness of the various identification colors to be used should be balanced to approximately equal apparent brightness between colors; as a design goal, variation between colors should be less than 2:1.

3.2.1.3 Coding

Indicator lights may be coded by color, shape, position and flashing. Color coding has application in normal white-lighted areas. Shape and flash coding are useful in low-level (red) lighted areas.

* Color coding should be used:

  a. To provide check reading capability for immediate assessment of system condition without the necessity for reading and evaluating the individual indications.

  b. To permit reduction in panel space requirements by time-sharing an indication of status, process, or alarm of a particular function within a single display area.

* Colors should be selected which best describe the information indicated and the operator response required for the operating mode of the particular equipment.

Color coding of indicator lights should conform to the criteria specified in Table 3-6. It is important to maintain a consistent philosophy of color coding throughout the system.

* Shape coding of indicator lights has limited application to FBM equipment; when used, symbols should be those which are common to system operation (e. g., the use of a circle for "Hatch Open" and a bar for "Hatch Shut"), provided that no more than fifteen different symbols are used.

* Flash coding should be limited to immediate action signals that indicate emergency or malfunction conditions. When used, flash rates should be limited to from 3 to 8 flashes per second, the "On" time being equal to the "Off" time. Flash duration should be at least 0. 05 sec.

Table 3-6

Color Coding for Indicator Lights

Information Indicated	Response Required	Color to Use+
Equipment is ready; or operation is satisfactory; or operation is completed successfully.	Continue operational procedures (if any).	Green
Emergency condition	Proceed immediately to casualty or malfunction sequence of activities; or use alternative equipment or method; and/or initiate repeat of operation or repair of equipment.	Red
Operation is in-process	Wait for operation complete indication before proceeding.	Yellow
Command to take action	Take immediate action indicated by legend or previous training.	Blue
Information is transmitted without any of the above connotations	None; or as indicated by legend or previous training.	White ++

+Chromaticities for Indoor Console Signal Lights (as measured in darkness; points a, b, c, and d, when joined (a-b, b-c, c-d, d-a) form irregularly shaped areas which define the boundary of acceptable chromaticities on a CIE diagram):

Color	Targets		LIMITS							
	x	y	a		b		c		d	
			x	y	x	y	x	y	x	y
Blue	.160	.130	SL[a/]	.125	.147	.197	.201	.197	SL	.035
Green	.250	.600	.200	.650	.300	.600	.350	.500	.250	.550
Red	.670	SL	.655	.335	SL	.335	.735	SL	.730	SL
Yellow	.560	.435	SL	.450	.550	.440	.590	.403	SL	.400
White	.490	.415	.450	.385	.450	.420	.500	.430	.500	.397

[a/]Spectrum Locus (where intersected by other of coordinate pair)

Luminances for Indoor Console Signal Lights (as measured in darkness; closest possible adherence to expressed ratio is very desirable)

Color	Targets (foot-lamberts)	Limits	
		Min.	Max.
Blue	1	.75	1.5
Green	10	7.5	15.0
Red	20	15.0	30.0
Yellow	60	45.0	90.0
White	30	22.5	45.0

++ The information to be transmitted via the illumination of a white indicator light must be clearly stated in its associated legend, except where previous training will insure that its meaning is not confused with the meaning associated with other colors.

* Switch-display units should be distinguished from indicator lights by the use of a black oval or round mask which is applied to the front surface of the display.

3.2.1.4 Legends

All indicator lights must be properly identified by a panel label and/or legend inscribed on the display screen surface.

* When legends are to be inscribed on indicator lights to be used on operating panels, the display area should be capable of accommodating up to twenty-eight character spaces.

* Legends should appear as black opaque upper case letters and numerals on a lighted field; they should be distinguishable when the indicator is in the off mode.

* Spacing within legends should conform to the following specifications:

   a. Letters and numerals should be so spaced that the area between adjacent characters is approximately equal; an approximation of this requirement can be obtained if the space between characters in a given word is made equal to 1/2 the average width of the characters.

   b. Space between words should be equal to the average character width.

   c. Space between lines of characters should be equal to the height of the characters (unless space constraints prevent it).

* For size coding of legends, the following specifications should be used:

a. Critical or alarm indicators:

Character height	0.1875 in.
Height-to-strokewidth ratio	6:1 to 8:1

b. All other indicators:

Character height	0.1250 in.
Height-to-strokewidth ratio	6:1 to 8:1

* Legends should be so designed that they can be removed easily when necessary to effect field modifications or nomenclature changes.

3.2.1.5 Reliability

Two or more lamps should be used for each mode; the installation should be such that failure of one lamp dims only part of the display, the other part(s) of the display remaining brightly lighted.

* When less than two lamps are to be used, provisions should be made for lamp test circuitry.

* Single-lamp indicator lights should be used only when their failure will be obvious from the situation in which they are used.

3.2.1.6 Maintenance

* Lamps should be easily replaceable, without any necessity to remove panels, other equipment, or the unit itself or to use special tools for lamp replacement.

* Lamps used in indicator lights of a particular type should be the same.

* Indicator lights designed to serve the same function should be interchangeable, regardless of their location in the system.

* Indicator lights not designed to serve the same function should not be interchangeable.

* All indicator unit subassemblies designed for removal should be keyed or coded for part mating and replacement.

* When more than one type of miniature lamp is to be used, a color-coded lamp base insulator should be provided for ease of differentiation between lamp types (particularly if industry No. 327 and 328 miniature lamps are used).

3.2.2 Digital and Word Readout Displays

3.2.2.1 Dimensions

3.2.2.1.1 Display Surface

From the human factors standpoint, the over-all display area is relatively unimportant so long as there is adequate space for the characters.

3.2.2.1.2 Characters

* For sequential access digital displays (counters) character dimensions should conform to the specifications presented in Table 3-7.

* Counter digits should have a height-to-width ratio of 1:1 and a bold strokewidth which is approximately equal to 1/6 of character height: the minimum spacing between adjacent digits should be equal to the strokewidth, and the maximum spacing should be 1/2 of character height.

The height-to-width ratio is an important consideration in counter design because the curved surface of the drum and the movement of the display make it difficult to recognize the critical portions of the numeral, namely, the top and the bottom.

For random access digital and word readout displays, problems of background design are minimized as the size of numerals or letters increases.

Table 3-7

Counter Character Dimensions for Operator Viewing Distance

Viewing Distance	Dimensions (in.) Height+	Width	Stroke-width	Minimum Separation Between Numerals
	Normal Illumination (Above 1 ft L)			
28 in.	0.15	0.15	0.025	0.025
36 in.	0.19	0.19	0.032	0.032
60 in.	0.31	0.31	0.052	0.052
	Low Illumination (0.03 to 1.00 ft L)			
28 in.	0.22	0.22	0.037	0.037
36 in.	0.28	0.28	0.047	0.047
60 in.	0.50	0.50	0.084	0.084

+For reading distances less than 28 in., minimum character height should be not less than 0.125 in.

* Character height of numerals and letters for random access displays should be approximately 1/2 in. (adequate up to a viewing distance of 60 in.).

* Character height-to-width ratio for random access displays should be approximately 3:2.

* Strokewidth for illuminated characters on a dark background for random access displays should be approximately 1/8 of the character height. The stroke-width of dark characters on a light background should

be approximately 1/6 of character height. (The difference in strokewidth is based on the fact that illuminated characters appear wider than they actually are because of the irradiation effect.)

- * Characters should be spaced no less than 1 strokewidth apart and no more than 1/2 character height on displays which present more than one character simultaneously; the minimum spacing between words should be the width of one character.

3.2.2.2 Illumination

Character displays should be legible at all levels of ambient illumination. The surfaces of surrounding areas should have a dull finish to reduce glare. Shadow, glare and cross-talk within the display area should be minimized.

- * For mechanical counters, the brightness of the background should be above 1 ftL under normal conditions and not less than 0.03 ftL under conditions of low ambient illumination.

- * Digits should be black on a white background in order to provide maximum contrast (except where color coding is used, such as a reverse color to indicate the least significant digit of a counter).

- * Counters should be self-illuminated if possible. Characters should appear as close to the plane of the panel surface as possible in order to provide a maximum viewing angle and reduce shadowing effects. (32, 49, 66, 82, 84, 90)

- * For random access devices, the brightness contrast for characters that are either brighter or darker than the display background should be maintained at a level which provides a probability of detection greater than 99 per cent, at a contrast ratio greater than 10 per cent. +

+ This can only be determined by trying out the unit under conditions approximating those expected under actual operating conditions.

* For projection-type devices, the position of the lamp filament should not affect legibility.

3.2.2.3 Coding

* Digital and word readouts can be coded by color or by size. However, color coding should not be allowed to interfere with character legibility or contrast.

3.2.2.4 Legends

* Character digital readout displays should be so designed that the numerals used read from left to right in order of decreasing magnitude; an in-line presentation is preferred to a random array.

* The number of significant digits displayed should be no greater than the accuracy of the input to the unit. If the right-hand drum of a counter has little value in relation to its function, it should be replaced with a stationary zero.

3.2.2.5 Reliability

* Counters should be so designed that the numbers snap into position without blur caused by rapid movement; similarly, bezel openings should be so designed that adjacent numbers on the drum do not appear above or below the digit being displayed.

Random access digital and word readout devices in which characters are stacked, such as gas tubes or edge-lighted plates, should be so designed that cross-talk is eliminated.

* Digital and word readout displays should be so designed that nonoperation or failure is readily apparent. The following techniques are useful in this regard:

a. Illumination (by edge-lighting, rear-lighting, wedge-lighting, etc.) when units are operational.

b. Physical impairment of view or absence of a reading when units are nonoperational.

c. Movement of an element of the display as a positive indication of operation; such movement should be rapid enough to be discernible and should be present at all times. However, care must be taken that other design criteria such as rate of information presentation, "snap" action, etc., are not violated.

3.2.2.6 Maintenance

Minor maintenance of the component should be accomplished from the front of the unit (e.g., lamp replacement).

3.2.3 Scalar Displays

Although scalar displays can be used to present a variety of data, the discussion presented here is concerned particularly with quantitative use of these displays.

3.2.3.1 Scales

3.2.3.1.1 Scale Marker Dimensions

The dimensions in Figure 3-22 should be used as models for the relative dimensions of major, minor, and intermediate graduations of scalar displays, and particularly of the size of the marked interval. The scale dimensions used are applicable to instruments and other types of scalar displays in which the primary requirements are for accuracy and rapidity of reading under a wide range of illumination. (Dimensions given in Figure 3-22 have been calculated for an assumed reading distance of from 20 to 28 in.)

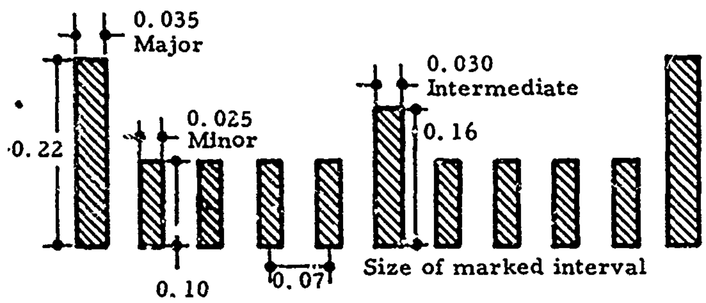


Fig. 3-22. Scale marker dimensions.

* Marker height-to-separation (size of marked interval) ratio should be from approximately 1:1 for minor markers to 2:1 for major markers, the distance being measured from graduation mark midpoints; the ratio should never exceed 5:1.

* Ratio of major mark height to intermediate mark height should be approximately 3:2; the ratio of intermediate mark height to minor mark height should be approximately 3:2.

* When the size of the marked interval is greater than 0. 07 in., minor marker thickness of stroke-width should be approximately 35 per cent of the size of the marked interval; whenever the size of the marked interval is less than 0. 07 in., minor marker thickness should be about 25 per cent of the size of the marked interval.

3. 2. 3. 1. 2 Scale Numbers and Numerical Progression

* All major scale divisions should be numbered according to the "Good" or "Fair" numerical

progression shown in Table 3-8; minor and intermediate scale divisions should not be numbered.

Table 3-8

Numerical Progression for Linear Scale Displays(4)

Good					Fair					Poor+			
										30	60	90	120
5	10	15	20	25	20	40	60	80	100	40	80	120	160
10	20	30	40	50	200	400	600	800	1000	0	2.5	5	7.5
50	100	150	200	250						0	15	30	45
100	200	300	400	500						0	60	120	180

+ Except for heading indicators with cardinal directions (north, east, south, west points) or other displays when operating doctrine specifies conditions of time scales or turn rates.

* An optimum scale design has the major numbered graduation marks at each interval of 10, and minor unnumbered division marks at each interval of 5.

* Readings should not appear in decimal form. If decimals must be used, the zero in front of the decimal point should be omitted.

* For ease in reading quantitative values, the area of most frequent or critical reading should be at the "nine o'clock" position. For bearing, course, or other right-left readings, the area of most frequent or critical reading should be at "twelve o'clock"; a dial that can be rotated manually may be used.

* If plus or minus values are to be displayed around a zero position, the zero should be located at the "nine" or "twelve o'clock" position.

* Critical markings should not be located at either end of a straight scale.

* Numbers should be located on the side of the graduation mark that is opposite the position of the pointer, provided that numbers will not be obscured by the instrument bezel (the latter consideration should take precedence over the former).

3.2.3.1.3 Interpolation and Graduation Interval

* Interpolation between scale markers should not be necessary for scales that are to be read quantitatively. Readings should be possible to the nearest graduation mark.

* Graduation mark spacing should be maintained at more than 0.07 in.; hence, some minor and intermediate graduation marks may have to be omitted. In general, a sufficient number of marks should be provided to limit interpolation to accuracies no greater than 1/4 of the space between two marks. (Fig. 3-23)

The midpoints on the compressed scale are only 0.04 in. apart. This is 0.03 in. less than the recommended minimum. In situations such as this, one must then design a scale in which interpolation is necessary. A satisfactory solution is shown below. The scale compensates for the 2-in. scale length restriction without reduction in legibility and readability and with only a slight reduction in intelligibility. This scale has a graduation mark spacing of 0.08 in., which approximates the recommended spacing and is more acceptable. Also, this scale requires only a simple interpolation of one unit between graduation marks.

* When space restrictions compress scales to the point where minor and/or intermediate

graduation marks must be omitted, use graduation intervals of 1, 2, or 5, or decimal multiples thereof.

Interpolation in tenths should be used only if errors as large as 10% of the interval can be tolerated in 50% of the readings.

* When scale interpolation is required, a staircase scale may be used in which the unmarked scale graduations increase in length from the lower numbers to the higher numbers between numbered major graduation marks. However, no more than five divisions between major marks should be used. (Fig. 3-23)

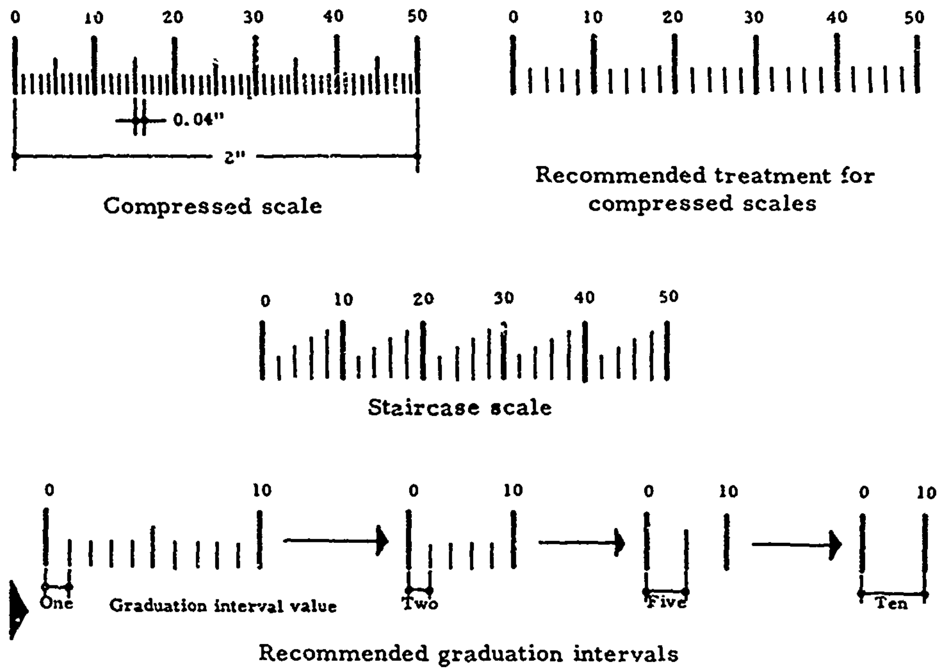


Fig. 3-23. Separation of scale markers.

3.2.3.1.4 Multiple and Nonlinear Scales

* Except for test equipment that must be capable of covering a wide range of measurements, each dial should be restricted to one quantitative scale and not more than two qualitative or check scales.

* Nonlinear scales should be avoided if possible; determination of reading values is more difficult and less accurate than when linear scales are used.

* Except on multirevolution instruments, a break should appear between the beginning and the end of circular scales.

* Except for tracking displays, most of the moving dial should be covered, the aperture being sufficiently large to permit at least one numbered graduation to be visible at each side on any setting. When the dial is used for tracking purposes, the entire dial face should be exposed.

* Except in red-lighted areas, dark indices should appear against a light background, rather than light indices against a dark background.

3.2.3.2 Pointers

* Full-visibility pointers on dials should be provided with a fine tip having a long taper that starts at the center of the dial.

* For vertical and horizontal straight scalar displays, where the exposed portion of the pointer is necessarily restricted by the rectangular configuration of the display, a flag, spade, or target pointer should be used.

* Pointers should be so mounted that their tips are aligned with the graduation markers on approximately

the same plane. Parallax can be compensated for by use of an indented dial design which raises scale markers and aligns pointer and scale on the same plane.

* Pointers should be located to the right of vertical scales and at the bottom of horizontal scales.

* Dual-pointer instruments should not be used. When necessary to display gross and fine values in the same scalar display, the pointer and scale should be used for the fine readings, and a counter for the gross readings.

3.2.3.3 Illumination

* Internal illumination should be provided for all scalar displays that are to be used in low ambient illumination environments (i.e., in which the display brightness is less than 1.0 ft L). When internal instrument illumination is to be used in areas having low-level red ambient conditions (i.e., from 0.02 to 0.08 ft L), such illumination should be in conformance with Detail Specification and Plan, BuShips, 9-S-C-4953L, Rev. 24. (32, 41, 49, 66, 67, 82, 84, 90)

3.2.3.4 Coding

Color, shape and position coding may be used on scalar displays so that monitoring can be accomplished readily and with minimum error.

* When an instrument must present accurate quantitative information occasionally, but is ordinarily check-monitored, coding should be incorporated into the dial design.

* When a scalar display indicates various zones of operating conditions, each zone may be color-coded, or scale markers associated with the zones

may be shape-coded. (However, under low-level red-light conditions, color coding should not be used.)

* When a scalar display contains a zone of readings that indicate normal operation, the zone may be color-coded (i.e., green), or the scale markers that bound the zone may be color- or shape-coded. In addition, if readings beyond the normal zone represent dangerous or limiting conditions, the portion of the scale or the markings that delimit the normal zone may also be color-coded (i.e., "Yellow: caution," or "Red: danger").

In addition to the coding techniques previously discussed in this section, two coding methods particularly applicable to scalar displays are those which involve use of a mechanical flag or a rotating disk. The mechanical flag method is that commonly used in aircraft instruments; the rotating disk method, although less common and not available in commercial manufacture, is readily incorporated into dial design, as shown in Fig. 3-24.(51)

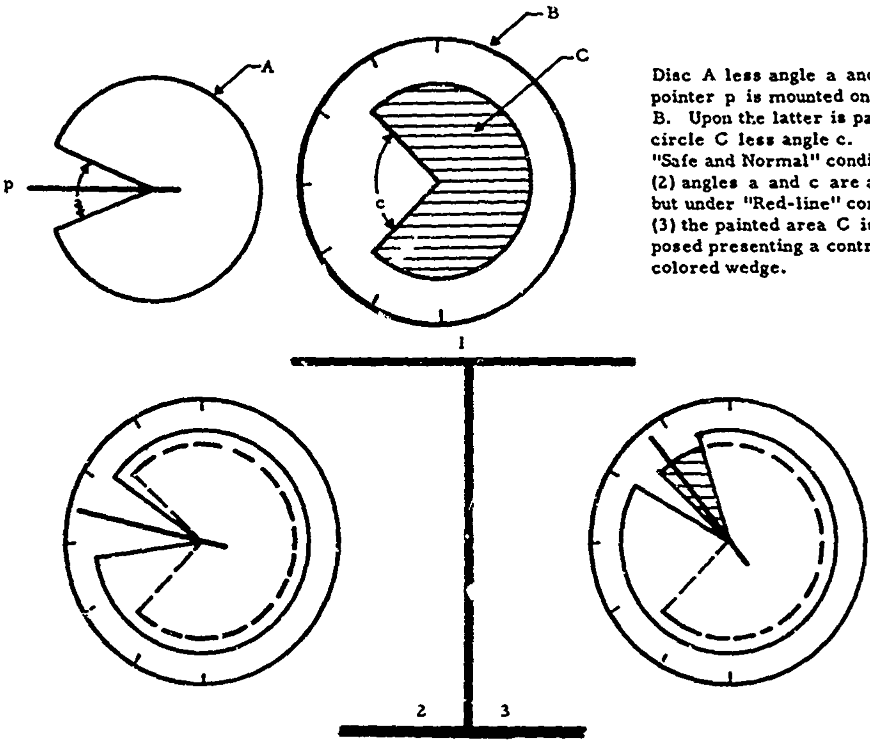
3.2.3.5 Legends

* Alphanumeric markings used in conjunction with scalar displays should be designed in conformance with the panel markings.

3.2.3.6 Reliability

* Positive indication of operation of the unit can best be provided by provision for comparison of display movement with associated backup components, such as indicator lights. In special cases, a flag or other signaling means may be provided.

* Where a high degree of information accuracy is required, the taut-band suspension or equivalent meter movement design should be specified in preference to conventional jewel and pivot suspension since the latter technique provides unsatisfactory results when the instrument is subjected to continued vibration or shock.



Disc A less angle a and with pointer p is mounted on disc B. Upon the latter is painted circle C less angle c. Under "Safe and Normal" conditions (2) angles a and c are aligned, but under "Red-line" conditions (3) the painted area C is exposed presenting a contrasting colored wedge.

Fig. 3-24. Descriptive drawing of experimental dial coding design.[51]

3.2.3.7 Maintenance

* Meter movement designs that minimize the need for calibration should be specified. The zero adjust feature on many meters aids calibration and is a desirable method of conforming to this requirement.

3.2.4 Cathode Ray Tube Displays

3.2.4.1 Signals and Background

The design of the basic CRT is dependent upon the type of display to be provided. In general, there is no significant difference between large and small tubes, from a human factors standpoint, except that a large tube makes it possible to use more detail in grid overlays. However, the time necessary to scan a large tube may be impractical, and a small tube with less detail may suffice.

* In general, scopes of 5- to 7-in. diameter are adequate when plotting is not required.

* Small scopes of 2- to 5-in. diameter should be used only for infrequent calibration or tuning purposes, since detail of signals in such displays is usually not adequate for frequent monitoring purposes.

* When plotting, tracking, or simultaneous viewing by several operators is required, scopes of at least 10- to 12-in. diameter should be used.

3.2.4.1.1 Signal Size

* Signal size of details presented on CRT's should be greater than 3 sq min of visual angle. Visibility of signals continues to improve as area increases, up to at least 10,000 sq min of visual angle.

3.2.4.1.2 Contrast

Signal to background contrast required for 99% probability of detection is dependent upon the size of the signals and the background brightness provided. Moreover, detection is enhanced if the level of background brightness is distributed evenly. (Fig. 3-25)

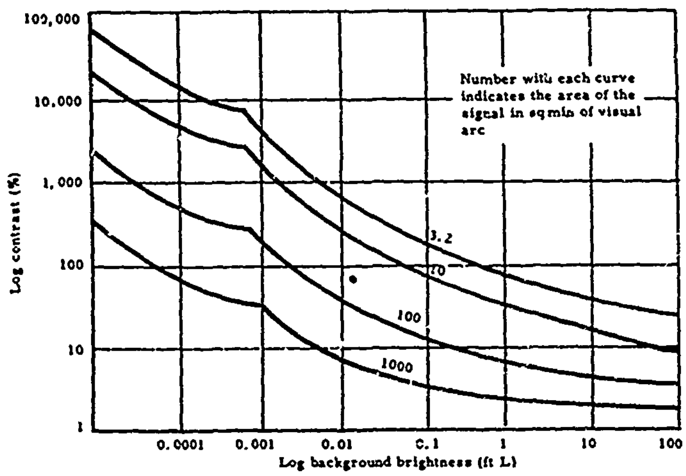


Fig. 3-25.- CRT signal-to-background contrast required for 99% probability of detection.[4]

3.2.4.1.3 Duration

* The visibility of dim signals is partially a function of the length of time they are exposed. For target detection (e.g., a radar target) on CRT displays, signals should appear for a minimum of 0.1 sec; the maximum duration of any signal need not be more than 1 sec.

3.2.4.1.4 Illumination

* Scope background brightness should approximate pre-exposure ambient brightness levels; in any case, ambient illumination to which the operator has been exposed during periods of adaptation should not exceed a level of 100 times that of the scope brightness.[6]

* In red-lighted areas, the use of red scope signals should be considered. Although no true red phosphors are commonly available in radar scopes, the P-19 and P-14 phosphors can be used.[6]

3.2.4.2 Coding

Conventional radar displays, sonar displays, or wall plotting boards generally present two dimensions of information, such as range and bearing (PPI), range and signal strength (A-scan), range and azimuth (B-scan), azimuth and altitude (C-scan), or azimuth error and altitude error (F-scan). Other combinations of dimensions may also be used.

3.2.4.2.1 Range Indication

Radar and sonar displays generally measure range radially from the transmitter/receiver in a polar coordinate system.

* Range mark interval scale should be represented as part of a scale which starts at zero, with numbered marks progressing by ones, twos, or fives and with the appropriate number of zeros after each digit. In general, progression by ones (i.e., 1, 2, 3, or 10, 20, 30) is superior to the other acceptable numbering systems.

* In order to minimize range mark identification errors when more than five range marks appear on a display, every fifth mark should be brighter or bolder than the others.

Range is sometimes measured by electronic range cursors or by pantographs, the latter being superior in both speed and accuracy. When a pantograph cannot be used but speed and accuracy are important, range rings (or marks) are acceptable. When accuracy alone is essential, range cursors are preferred to range rings.

Fig. 3-26 shows per cent of readings in error as a function of number of range rings used. These data apply to operators who are reading ranges as rapidly and accurately as possible. The range rings were optimally scaled, i.e., every fifth ring was discriminably different from (thicker than) the others. Time required to determine the range of each signal is also included.

3.2.4.2.2 Bearing Indication

Bearing can be indicated by overlays, bearing dial estimates, a bearing dial and cursor, a bearing counter and cursor, or a pantograph. The pantograph method provides highest speed and accuracy.

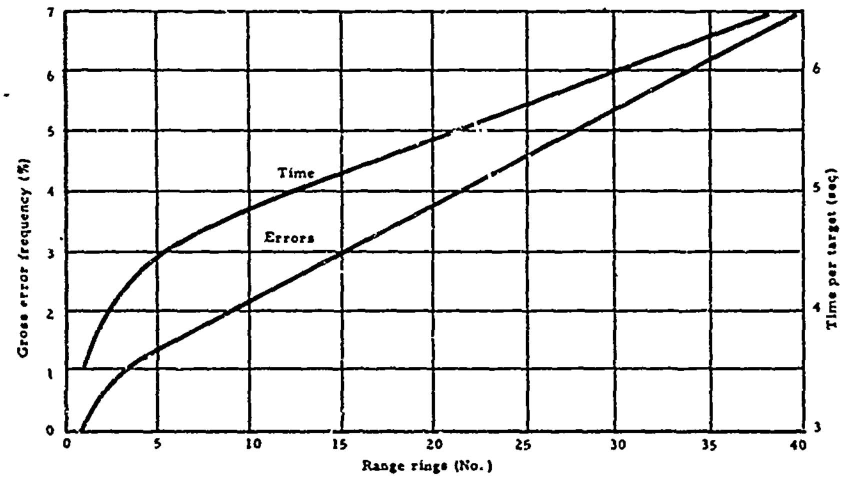


Fig. 3-26 Expected reading error using range rings.(4)

3.2.4.2.3 Symbols

The presentation of a radar display or other cathode ray tube presentation can often be enhanced when a geometric symbol is portrayed in association with the pip.

* Symbols used should be selected from among those shown in Figure 3-27. (12)

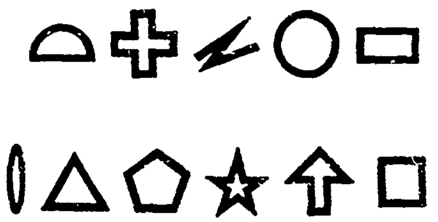


Fig. 3-27. Recommended symbols for use on CRT displays.(12)

* Under adverse display conditions, no more than six symbols should be used.

* Symbols should be approximately 1/2 in. in height and should have a strokewidth from 1/8 to 1/10 of their height. When small symbols are used, the strokewidth-to-height ratio should be 1·10, or less, provided that strokewidth is not less than 0. 02. Large symbols should be used when display conditions are unfavorable (i. e., much visual noise).

* Symbols which are to occur infrequently should have the most distinctive shapes to facilitate recognition.

* When symbols are combined to provide a complex message capability, the following criteria apply:

  a. Combinations normally should not exceed two geometric symbols, a location dot, and a speed-direction vector line. (Fig. 3-28)

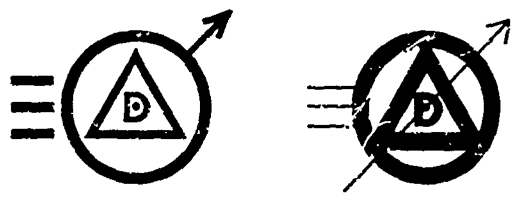


Fig. 3-28. Good and bad practice in symbolic code construction.[12]

  b. Primary symbols should be large and enclose a space.

  c. No auxiliary symbol should cross, distort, interfere with, or in any way obscure the primary symbol.

d. Symbols used should conform as closely as possible to stereotyped meanings normally associated with such symbols.

3.2.4.3 Overlays

The addition of overlays to cathode ray tube scopes lessens visibility by from 3 to 7 db, the extent of loss increasing as edge-lighting is increased and/or the surface becomes dirty. No known compensation for such a loss in visibility can be made. However, this degree of loss in visibility is usually acceptable.

3.2.4.4 Reliability

Failure in circuits which modulate the sweep of a cathode ray tube display are often difficult to detect, although, in some cases, circuit monitoring can provide a positive indication of operation.

* An on-indicator should be provided on the equipment which generates the display. Where practical, a representation of the sweep should appear on the face of the display.

* An indication of poor adjustment should be provided (except on test equipment) when there is a signal in the equipment that is not visible on the display face.

It is recommended that a signal generator be provided with radar/sonar type equipment so that the operator can conduct visibility tests during operation. For any given set of operating conditions, the operator can then adjust the CRT bias and other electronic variables so that the settings will permit detection of the weakest signal which may be expected. This is particularly helpful in search radar where targets are rarely available for such adjustments. The optimum CRT bias setting for any piece of equipment depends upon video gain, antenna rotation rate, pulse repetition frequency and random noise levels.

3.2.4.5 Maintenance

For maintenance considerations in the design of CRT displays, see the section on Design of Equipment for Maintenance.

3.2.5 Printers

Human factors guidelines considered here in relation to printers pertain primarily to the printout or hard copy produced by such devices.

3.2.5.1 Materials

3.2.5.1.1 Paper

* Hard finish matte paper should be used to avoid the problems of smudged copy and glare.

* Thin, transparent paper should not be used.

* Paper hold-downs should be provided to reduce paper vibration.

* Accordion-fold paper should be used, particularly if record search is required.

3.2.5.1.2 Ink

* Black ink should be used on white paper to provide maximum contrast.

3.2.5.2 Imprinting

* Capital letters should not be used for long passages of copy.

* For emphasis in short passages of copy, capitals, bold face, or italics should be used. Bold face type, if legible, has no effect on reading speed; however, italic type is read 3 per cent slower than is Roman type, and capital letters are read 12 per cent slower than are lower case letters.

* Type should be of uniform strokewidth and of a style that terminates without serifs (e.g., Gothic or Futura).

* Preferred height-to-strokewidth ratio should be within the range 6:1 to 8:1 (see Table 3-16, page 206) for adequate legibility under normal conditions (i.e., 5 to 20 ft C) of illumination. When pressure-sensitive paper is used, bold type having a ratio of 1:5 may be required if the contrast would otherwise be less than that which a black print ribbon can provide.

* Average width of characters (letters and numerals) should be between 65 per cent and 80 per cent of their height. Wider characters (up to 1:1 height-to-width ratio) are permissible, but require more space, and, therefore, are not practical for most printer applications.

* The distance between lines of type (i.e., the leading) should not be less than 2 points when 10- or 11-point type is used.

* Line length should not exceed 4.6 in. or be less than 2.3 in. The preferred line length is 3.50 in. (21 picas). Two or more columns should be used, if necessary.

* Margins at the edges of the paper should not be less than 1/2 in. in width. (Larger margins do not aid legibility and hence only result in a waste of printing surface.)

* Determination of type sizes to be used in displays to be viewed at selected distances should be based on the data provided in Table 3-9.

3.2.5.3 Coding

Coding by numerals, letters or other symbols is particularly applicable to printer readouts. (Other coding methods can be used in conjunction with printers, subject to criteria discussed in connection with visibility of visual displays.)

* Coded or abbreviated information reduces space, but places increased demands on character contrast

Table 3-9

Type Point Size and Viewing Distance

Viewing Distance (inches)	Type Point Size (for Century, Futura-Medium, or equivalent fonts)+
up to 28	12
28 to 43	18
44 to 55	24
56 to 72	36

+ The point size of any type can be determined by dividing 72 by the number of lines per column inch. (E. g., 12 lines per column inch = 6 point, 9 lines = 8 point, etc.)

and resolution, since the loss of recognition of a single character may make the message ambiguous.

* Coding by printed symbols, other than letters or numerals, should be limited to fifteen steps, since it becomes difficult to train operators to interpret additional steps.

3.2.5.4 Illumination

* The display should be illuminated by supplementary or integral lighting.

* If a transparent cover or viewing window is to be used, care should be taken to insure that no glare or specular reflection results.

Elimination of such a problem can be accomplished by use of lighting under the cover glass (i.e., between the cover glass and the display itself).(32, 41, 49, 66, 82, 84)

3.2.5.5 Noise

* Sound baffles should be used to minimize sound generated by printer operation. Ambient noise resulting from printer operation should be less than 50 db.

3.2.5.6 Reliability

* A paper advance control should be provided to enable the operator to read the most recently printed line.

* Positive indication should be provided of the need for replenishment of materials; a preferred technique for indicating the amount of paper remaining is to use a footage counter on the printer, an alternative technique being the use of markings on the last 20 per cent of the paper.

* Indicator lights should be provided to show both equipment status and mode of operation; typical of the information to be displayed in this fashion are "Printer Off," "Printer Standby," "Automatic Input," or "Manual Input."

3.2.5.7 Maintenance

* Provisions should be made for the loading of paper without the need for major disassembly or the use of special tools. A spare paper supply should be provided.

* In units which use a hammer and typewheel mechanism, ribbon replacement should be conveniently accomplished without extensive disassembly; ribbon magazines can be used for this purpose. Normal ribbon change (i.e., reversal) should be automatically accomplished.

* Printing mechanism should be recessed to maximize operator safety and to minimize damage to the mechanism.

* Front access should be provided for visual and maintenance checks.

3.2.6 Recorders

Design of individual recorders for specific applications must be determined on the basis of such factors as necessary channel capacity, frequency response, etc.

* Rectilinear coordinate traces should be used whenever possible. Adequate reference lines should be provided for determination of variable values without manual aids, scales, etc.

* Trace width should be adjustable. In lightbeam types of recorders, spot intensity should be controllable; in ink-writing types, fluid flow should be adjustable; in heated stylus units, stylus heat should be variable.

* Overlapping traces should be avoided; the width of each channel on the recording surface should be adequate for the desired accuracy and range of the record.

* Slewing speeds should be provided which permit rapid and accurate positioning and/or calibration of marking devices.

* Scales should be provided to give immediate indication of changes in both magnitude and direction.

* A time marker should be provided that is independent of chart drive.

* Controls should be provided for chart alignment. On plotters, X and Y controls should be clearly differentiated by proper grouping.

* Provision must be made to take up used paper—accordion-fold paper is preferred for record review purposes and a paper hold-down mechanism should be provided. Paper positioning should be easily achievable without removal of covers, etc.

3.2.6.1 Coding

* If multiplexing of a single channel is employed, coding should be used to distinguish the variables (e.g., dots, dashes, dot-dashes, symbols, etc., may be used).

3.2.6.2 Illumination

* The trace should have adequate contrast with the chart on which it is recorded. In red-lighted areas, only black should be used for trace symbols and coordinate lines.

* Recorders to be used in low-level (red) lighted areas should have a recorder surface that has an adjustable brightness level between 0.1 and 1.0 ft L with uniform brightness over the entire surface.+

* Where no dark adaptation is required, at least 5 ft L chart brightness should be provided with some method of integral illumination.+

* If a transparent cover or viewing window is used to protect the recording surface, it should not produce glare spots or specular reflection from ambient illumination. If supplementary illumination is used, it should be introduced below the cover glass.

3.2.6.3 Reliability

* Indicator lights should be used to show both recorder status and mode of operation.

* Provision should be made for notifying the operator when materials should be replenished. Paper needs can be shown either by a remaining footage counter or by imprinting of the last 20 per cent of the paper.

+ See Table 3-2: Display Lighting, page 48, and references 32, 4[illegible], 49, 66 82, 84.

3.2.6.4 Maintenance

* Access to the recorder should be provided for visual check, maintenance and replacement of parts, fuses, etc., and for lubrication.

* Paper loading and ink replenishment should be accomplished without the use of special tools or major disassembly of the recorder.

* Fume producing writing techniques should be properly vented to the ship's air purifier system (such devices should be avoided, if possible, for shipboard application, since they require an adiditional load on the ship's air purifier system).

* Spare paper and ink supplies should be provided within the recorder equipment or should be located nearby.

* Chart cutting aids should be provided.

* The packaging technique for submarine application should provide front access for lower echelon maintenance and provision for easy replacement of plotting paper and ink, etc., as well as over-all dimensions which will allow for removal through a submarine hatch for higher echelon maintenance.

3.3 Auditory Displays

Design criteria generally applicable to the design of auditory displays include the following:

* Auditory signals should be at least equal to, preferably greater than, the ambient noise level; otherwise, signal pitch and/or quality must be relied upon for discrimination.

* When tonal discriminations must be made, signals having principal frequencies in the range of 1,000 to 2,400 cps should be used. Warbling tones provide good signal discrimination.

* For emergency and warning indications, use of a two-stage auditory presentation should be considered; in such installations, the first stage usually is a warning bell, buzzer, etc., whereas the second stage consists of a brief recorded verbal announcement.

* Auditory display designs should provide for feedback of the signal to the originator or for acknowledgment by recipients. In the absence of either of these, the equipment should generate an alternate signal.

II. CONTROLS

1. Description

Controls may be classified in terms of the movement involved and in terms of the types of hardware which are used.

In terms of movement, controls may be categorized on the basis of whether their action is discrete or continuous. Discrete action controls can be set at any one of a limited number of fixed positions. Both actuate and select types of controls are categorized in this group. Continuous action controls can be set at any position between the limits of movement of the control; the adjustment type of control would be categorized in this group.

1.1 Hand Controls

1.1.1 Discrete Action Controls

Since discrete action controls may be set at any one of a limited number of exact positions, they are used for applications that involve turning equipment on or off, the selection of modes of operation, the choice of appropriate meter scales, etc. The types of discrete action controls discussed in this subsection include the following:

a. Push buttons.

b. Toggle switches.

c. Rotary selector switches.

1.1.1.1 Push Buttons

Hand push buttons are two-position controls; they may be used individually or combined for special applications such as keyboards and matrices. Two types of hand push buttons are recommended for use in the FBM system: latching (push-on/lock, push-off) and momentary contact (push-on and release-off) push buttons. The use of alternate action (push-on and push-off) push buttons is not recommended unless an associated status indicator is used. (Fig. 3-29.)

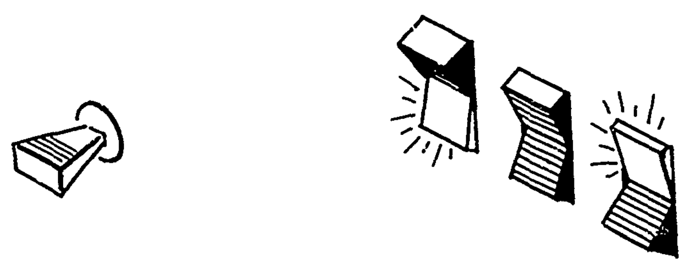
Finger operated

Thumb or hand operated

Fig. 3-29. Push buttons.

1.1.1.2 Toggle Switches

Toggle switches may be either two- or three-position controls and may be momentary (spring-loaded) or locking in their action. Toggle switches use either a lever or a rocker type of action. Lever-action toggle switches may be positive-action or spring-loaded controls. Rocker-action switches use two control faces which meet at an obtuse angle, the face that is depressed indicating the present position of the control; switch position is changed by applying force to the opposite face until it is depressed and locked into position. (Fig. 3-30.)



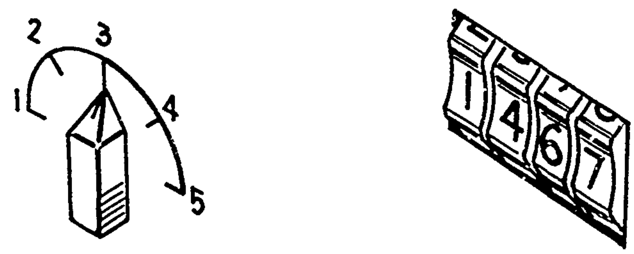
Lever action

Rocker action

Fig. 3-30. Toggle switches.

1.1.1.3 Rotary Selector Switches

Rotary selector switches have from 3 to as many as 24 control positions. They are operated by applying force to the switch knob until the switch snaps into the next position. Activation is indicated by an audible click and a tactual detent action. Rotary selector switches with movable pointers and stationary symbols are recommended for FBM equipment. Thumbwheel selector switches are also applicable where dripproofing is not required. (Fig. 3-31.)



Bar knob Thumbwheel

Fig. 3-31. Rotary selector switches.

1.1.2 Continuous Action Controls

The types of continuous action controls discussed in this subsection include the following:

a. Continuous position controls.

b. Handwheels.

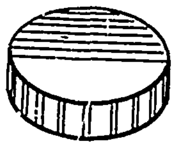
c. Handcranks.

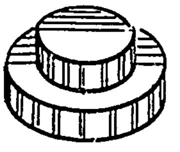
d. Levers.

1.1.2.1 Continuous Position Controls

Continuous position controls, or knobs, are used for making small turning operations which do not require the application of large

forces; they have an unlimited span of control movement and can be used for either gross or fine positioning over a wide range of adjustments. (Fig. 3-32.)





Single control

Ganged control

Fig. 3-32. Continuous position controls.

1.1.2.2 Handwheels

Handwheels are used for making turning operations where large rotary forces are required: they may be combined with smaller controls such as knobs and push buttons. For continuous control, handwheel movement should be limited to 120 deg; for discontinuous control, such as manual valve operations, movement is unlimited. (Fig. 3-33.)

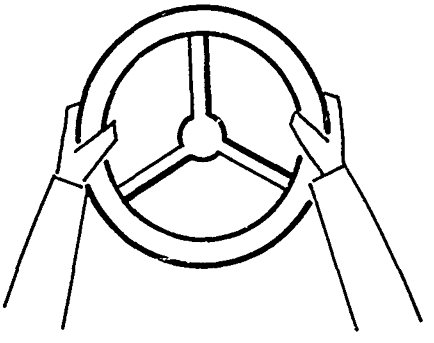


Fig. 3-33. Handwheel.

1.1.2.3 Handcranks

Handcranks are used for making turning operations where large distances are covered and high rates of turning are required; they may be attached to knobs or handwheels. Handcranks have an unlimited range of control movement and may be used for either gross or fine positioning over a wide range of adjustments. (Fig. 3-34.)

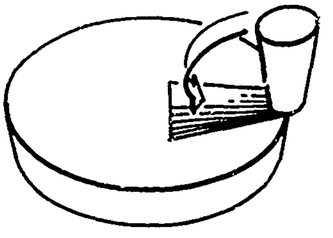
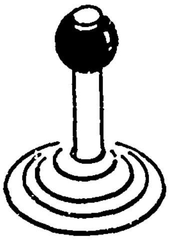


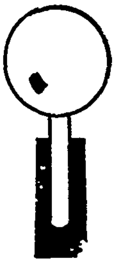
Fig. 3-34. Handcrank.

1.1.2.4 Levers (including small joystick controls)

Levers are used for making linear movements; they may be either one- or two-dimensional controls. Control movement is normally limited to ±45 deg from the vertical position in order to minimize hand movement. Precise positioning over a wide range of adjustments can be provided only if rate aiding is added. (Fig. 3-35)



Joystick



Simple lever

Fig. 3-35. Levers.

1.2 Foot Controls

1.2.1 Foot Push Buttons

Foot push buttons are comparable to hand push buttons in that they are two-position controls. Only the momentary contact type of foot push button is recommended for the FBM system. The foot component is used when it is desirable to free the operator's hands for other tasks. Activation of the control should be indicated to the operator on an associated display. (Fig. 3-36.)

1.2.2 Pedals

Translatory pedals are the only type of pedal recommended for use in the FBM system; reciprocating and rotating pedals have no application to FBM equipment. Translatory pedals are continuous-action foot controls which are used to make linear movement; they have a limited range of control movement and cannot be used to provide precise positioning over a wide range of adjustments. Pedals cannot be operated with the speed and accuracy of hand controls, although more force can be applied when they are used. (Fig. 3-37.)

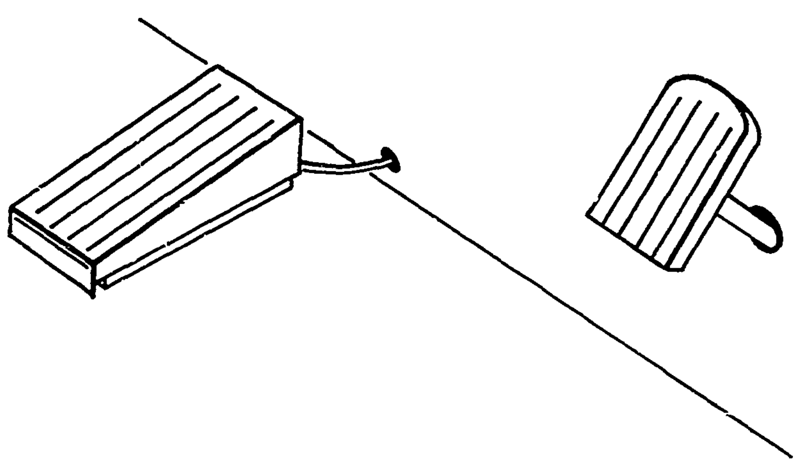


Fig. 3-36. Foot push button.

Fig. 3-37. Translatory pedal.

2. Selection and Utilization

2.1 General

The selection of specific controls to be used in each application can best be accomplished by consideration of such factors as the following:

a. Function, purpose, and type of change to be effected and the extent or direction of change to be required.

b. Speed, accuracy, range, and force requirements for control operation.

c. Information required by the operator to identify the control and its setting and to sense any change in control position.

d. Constraints imposed by the working environment.

2.1.1 Division of Work among the Body Limbs

Aspects of control selection and utilization that involve the assignment of functions to the body limbs are based on operational control requirements.

*[+] Controls that require rapid and precise setting should be assigned to the hands.

* Controls that require large or continuous forward application of force should be assigned to the feet.

* Assignment of controls among the body limbs should be so distributed that no single appendage is overburdened (e.g., no more than two controls should be assigned to each foot.

[+]The * symbol indicates specific guidelines for the selection and utilization of controls.

2.1.2 Compatibility with Controlled Object or Display

* Direction of control movement, in the case of linear or rotary controls, should be consistent with the movement of the controlled object or of the moving portion of the display.+ Table 3-10 provides examples of the types of relationships involved.

Table 3-10

Use of Linear and Rotary Controls with Various Types of Displays

Display		Acceptable Control	
Type	Example	Type	Example
Nonmoving (stationary)	Indicator light	Linear or rotary	Toggle switch or rotary selector switch
Rotary through an arc less than 270°	Moving pointer indicator	Linear or rotary	Continuous position or lever
Rotary through an arc more than 270°	Circular dial	Rotary	Crank
Linear in one dimension	Moving-scale indicator	Linear or rotary	Lever, translatory pedal, or handwheel
Linear in two dimensions	CRT	Linear or two rotary controls	Joystick or two cranks

+Direction-of-movement relationship between controls and displays is discussed in detail in the section Direction-of-Movement Relationships, page 189ff.

2.1.3 Conformity with Precision Requirements

Requirements for precision of adjustment impose additional considerations relative to control selection.

* For precise adjustment, hand rather than foot controls should be used.

* For medium adjustments of a controlled object over a narrow range, a linear or rotary control can be used. However, for high degree of precision over a wide range of adjustments, a properly geared multirotation control should be used.

* For precise adjustments along a continuum, or when many settings (usually more than 24) are required, continuous action controls should be used.

* For a limited number of settings, or when precision requirements are so gross that a limited number of settings can represent an entire continuum within the required accuracy, discrete action controls should be used.

2.1.4 Force and Range of Settings

* Force and range of settings must also be considered when controls are to be selected. Acceptable controls for various forces and settings are given in Table 3-11.

2.1.5 Combinations of Controls

Functionally related controls may be combined advantageously under certain circumstances. In such cases, reaching movements can be reduced, thereby aiding in the sequential or simultaneous operation of controls and economizing on the use of panel space for control mounting. However, when combined controls are used, special attention should be given to the hazard of accidental activation; e.g., for a dual control, knob diameters of 1/2 in. and 1-3/4 in. should be used.

Table 3-11

Selection of Controls as Related to Force and Range of Settings

Force and Setting	Acceptable Control
Small forces (3 lb. or less)	
2 discrete settings	Hand push button, foot push button, or toggle switch
3 discrete settings	Toggle switch or rotary selector switch
4 to 24 discrete settings	Rotary selector switch
Small range of continuous settings	Knob or lever
Large range of continuous settings	Crank
Large forces (greater than 3 lb.)	
2 discrete settings	Detent lever, large hand push button, or foot push button
3 to 24 discrete settings	Detent lever
Small range of continuous settings	Handwheel or lever
Large range of continuous settings	Large crank

2.1.6 Effects of Working Environment

Consideration should be given to those factors present in the working environment that may impose constraints on the type of control selected. Factors to consider may include, but are not necessarily restricted to:

a. Special clothing worn by the operator.

b. Workplace layout.

c. Restricted panel or console space.

d. Ambient illumination.

2.2 Discrete Action Control

* Selection of discrete action controls should be based on the information summarized in Table 3-12.

2.3 Continuous Action Control

* Selection of continuous action controls should be based on the information summarized in Table 3-13.

Table 3-12

Selection if Discrete Action Controls

Characteristics	Hand Push Button	Foot Push Button	Toggle Switch	Rotary Selector Switch
Time required to make control setting	Very quick	Quick	Very quick	Medium to quick
Recommended number of control settings	2	2	2-3	3-24
Space requirements for location and operation of control	Small to medium	Small	Small	Medium
Special design may be required to prevent accidental activation	No	Yes	No	Yes
Effectiveness of coding	Fair to good	Limited	Fair	Good
Effectiveness of visually identifying control position	Poor+	Poor	Fair to good	Fair to good
Effectiveness of operating controls simultaneously with like controls in an array	Good	Poor	Good	Poor
Effectiveness as part of a combined control	Good	Poor	Poor	Fair

+Unless control is back-lighted and light comes on when control is activated.

Table 3-13

Selection of Continuous Action Controls

Characteristics	Continuous Position Control	Hand-wheel	Hand-crank	Lever	Pedal (Translatory)
Large forces can be developed	No	Yes	Yes	Yes	Yes
Space requirements for location and operation of control	Small to medium	Large	Medium to large	Medium to large	Medium
Special design may be required to prevent accidental activation	No	Yes	Yes	No	Yes
Desirable limits to control movement	Unlimited	±60 deg	Unlimited	±45 deg.	Small
Effectiveness of coding	Good	Fair	Fair	Good	Limited
Effectiveness of visually identifying control position	Fair to good (for less than 360° rotation)	Poor to fair	Poor (for more than 360° rotation)	Fair to good	Poor
Effectiveness of non-visually identifying control position	Poor (for fine adjustments) to good (for coarse adjustments)	Poor to fair	Poor (for more than 360° rotation)	Fair to good	Poor to fair
Effectiveness of operating control simultaneously with like controls in an array	Limited	Poor	Poor	Good	Limited
Effectiveness as part of a combined control	Good (as ganged control)	Good	Poor	Good	Poor

3. Design

3.1 General

3.1.1 Control-Display Ratio+

The control-display (C/D) ratio is defined as the ratio of distance of movement of the control to that of the moving element of the display (e.g., pointer, cursor, etc.) or object (e.g., vehicle) being controlled. For position control (zero-order control), the position of the control directly affects the position of the controlled object, as described by the equation:

$$X_o = K_1 X_c \qquad \text{when } X_c = f(t) \tag{1}$$

where

X_o = the position of the controlled object,
X_c = the position of the control, and
$1/K_1$ = the C/D ratio.

For rate control, the position of the control directly affects the rate of movement of the controlled object, as described by the equation:

$$X_o = K_2 \int_0^t X_c \, dt \qquad \text{when } X_c = f(t) \tag{2}$$

where

K_2 = the gain

For rate-aided control, the position of the control directly affects both position and rate of movement of the controlled object, as described by the equation:

$$X_o = K_1 X_c + K_2 \int_0^t X_c \, dt \quad \text{when } X_c = f(t) \tag{3}$$

where

K_1 / K_2 = the aided tracking constant.

For linear and near-linear controls (e.g., levers) which affect linear displays, the C/D ratio is usually defined as the ratio of the linear distance of control displacement to the distance of a resulting display movement. Control displacement should be measured from the point where the operator's hand grasps the control. For small rotary controls (e.g., knobs) which affect linear displays, the C/D ratio is usually defined as the ratio of the number of control rotations to the distance of the resulting display movement. (Fig. 3-38)

+ For further reading on the design of man-operated continuous control systems, see Bekey(8) and Birmingham and Taylor(10).

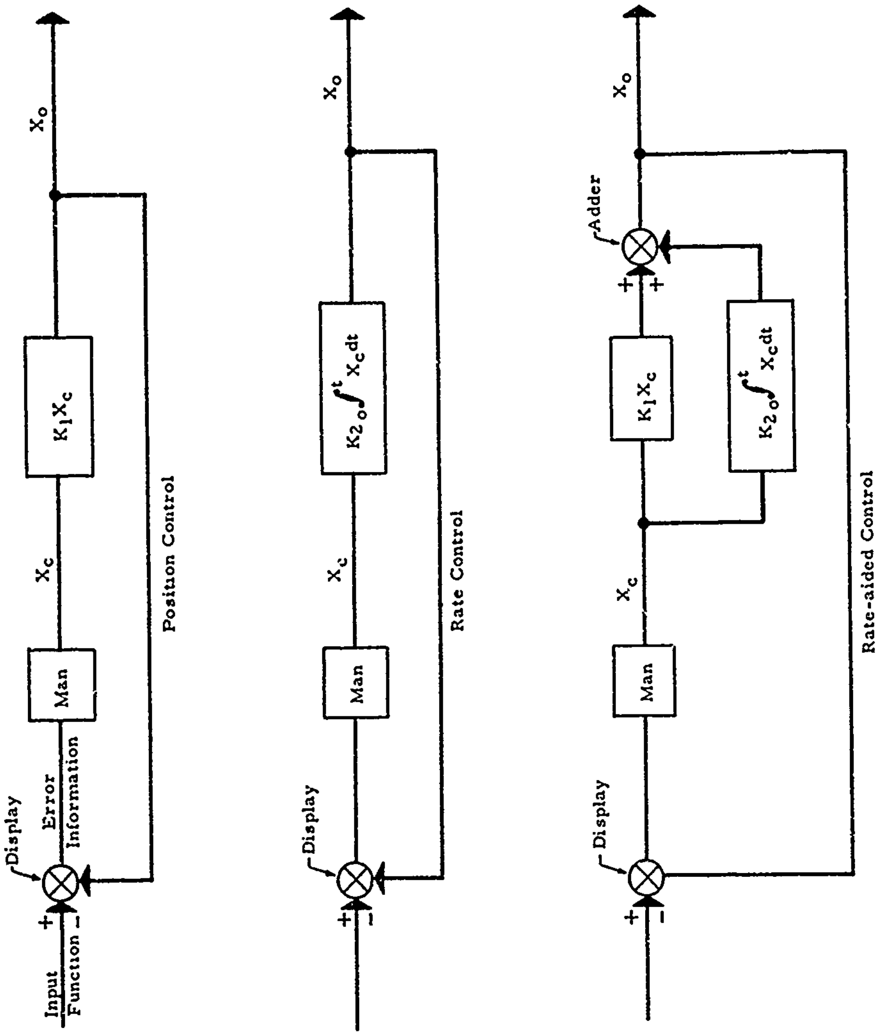


Fig. 3-38. Position, rate, and rate-aided control.

3.1.1.1 Optimization of C/D Ratio

The optimum C/D ratio minimizes the total time required to make the desired control movement. In positioning a continuous adjustment (nondetent) control, the operator first makes a slewing movement and then a fine adjusting movement. The total time required to make the control movement is the sum of the times required to make these two movements.

a. Slewing movement (also referred to as "travel," "gross adjusting movement," or "primary movement") is used to move a control rapidly close to the final desired position. An increase in the C/D ratio will increase slewing time because of the longer movements required. However, for linear controls, slewing time is only slightly greater for long movements than for short ones.

b. Fine adjusting movement (also referred to as "adjusting movement" or "secondary movement") is used to place a control precisely in the desired position. Fine adjusting time is reduced either by increasing the C/D ratio or by easing the tolerance requirements (i.e., increasing the maximum acceptable error in positioning the control).

3.1.1.2 Factors Which Affect C/D Ratio

3.1.1.2.1 Gear Ratio+

"Slewing" or "travel time" decreases, whereas "adjustment time" increases, as the gear ratio is increased. When both factors must be combined, e.g., by using a rotary control to make pointer settings, it has been determined that a ratio of about 1:2 is optimum. However, quite different gear ratios may be optimum for other control tasks.

+Gear ratio is defined as output/input.

3.1.1.2.2 Tolerance

Fine adjusting time is reduced directly by easing the tolerance requirements. Slewing time is probably also reduced because the operator tends to move his control into position more slowly when he knows that it will have to be positioned precisely. The optimum C/D ratio will be smaller if the fine adjusting time is reduced by a greater amount than the slewing time.

3.1.1.2.3 Display Size

With tolerance kept constant, changing the size of the display may increase total adjustment time.

3.1.1.2.4 Viewing Distance

Research to date suggests that viewing distance does affect performance and that it might also change the optimum C/D ratio, although no definite relationships have been established as yet.

3.1.1.2.5 Time Delays

The type and extent of any time delay in the system may affect the optimum C/D ratio. For exponentially shaped time delays occurring between the control movement and the resulting display response, within reasonable limits, the longer the time delay the smaller will be the optimum C/D ratio.

*[†] In many applied problems, the optimum ratio will be unique for the type of control task involved and, hence, the optimum C/D ratio should be determined empirically because it may be affected by gear ratio, display size, tolerance, viewing distance, and time delays.

3.1.2 Resistance

Some force must always be applied to make a control move. The type and amount of resistance offered by the control (and the device to which it is coupled) affect the operator's force requirements. The types of resistance to be discussed here include the following:

a. Spring loading (elastic resistance)

[†] The * symbol indicates specific guidelines for the design of controls.

b Static friction (stiction).

c. Viscous damping (fluid frictional resistance)

d. Inertia (inertial resistance).

e. Coulomb friction (sliding or kinetic friction)

Rarely, if ever, is control resistance of a single type, since most controls have some mass and, hence, some inertia. Many controls move on a slide, shaft, or pivot and have some static and sliding friction. In some cases, it is desirable to combine more than one type of resistance in a control. + For example, viscous damping may be helpful in counteracting the adverse effects of excessive inertia. Depending upon the type and amount involved, resistance can affect:

a. Precision of control operation.

b. Speed of control operation.

c. "Feel" of the control.

d. Smoothness of control movement.

e. Susceptibility of the control to accidental activation and to the effects of jolting, vibration, buffeting, g-forces, tremor, weight of the limb on the control, etc.

3.1.2.1 Spring Loading (Elastic Resistance)

Spring loading or elastic resistance has the following characteristics:

a. Resistance varies directly with control displacement, but is independent of velocity and acceleration.

b. Force is applied toward the null position when the control is displaced, thereby identifying the null position and aiding in making adjustments around it.

+Specific types of friction which should be employed with controls are described under the design sections for individual controls.

c. Sufficient damping is provided to minimize inadvertent activation due to accidental brushing against the control, jolting, g-forces, vibrations, buffeting, and hand tremor.

d. Smooth control movements can be made

e. Changes in direction and small changes in position can be made.

f. Feedback information ("feel") is provided about control velocity (although it is questionable whether or not this information can be used precisely).

3.1.2.2 Static Friction (Stiction)

Static friction or stiction has the following characteristics:

a. Resistance decreases sharply to a constant value when the control starts to move smoothly and continuously. The resistance is independent of displacement and acceleration.

b. Static friction tends to hold the control in position.

c. Static friction reduces the likelihood of undesired activation due to accidental brushing against the control, jolting, g-forces, vibrations, buffeting, and hand tremor.

d. Static friction increases the difficulty in making precise settings.

e. It is difficult to design the control to insure a constant amount of friction, but a "locking" device can be provided by which friction is readily adjusted.

3.1.2.3 Viscous Damping (Fluid Frictional Resistance)

Viscous damping or fluid frictional resistance has the following characteristics:

a. It varies directly with control velocity, but is independent of displacement and acceleration.

b. Quick gross movements are resisted.

c. Control returns automatically to the same (null) position when the operator's limb is removed making it ideal for a momentary contact or "dead-man" switch.

d. Low inertia allows for quick changes in direction.

e. The probability is reduced of inadvertent activation due to accidental brushing against the control, jolting, g-forces, large vibration, and buffeting.

f. Feedback information ("feel") is provided concerning control position.

g. Force gradient can be modified to provide special cues as to critical positions of the control (e.g., resistance suddenly increases as a null or limit is approached).

3.1.2.4 Inertia (Inertial Resistance)

Inertia or inertial resistance has the following characteristics:

a. The resistance varies directly with control acceleration, but is independent of displacement and velocity.

b. Sudden changes in velocity are resisted; smooth

control movements and gradual changes in velocity can be made.

c. Effects of small fluctuations in force are minimized, and high-frequency oscillations can be damped out.

d. Large forces must be applied in order to stop control movements quickly; hence changes in direction of movement may be hindered.

e. When combined with viscous damping, a basis is provided for discrimination of small changes in the rate and acceleration of the load.

f. Difficulty of making rapid, precise adjustments is increased because of the danger of over-shooting.

g. High inertia can be used to maintain control movement without requiring continual application of force (e. g., spinning a handwheel to its "Off" position).

3.1.2.5 Coulomb Friction (Sliding or Kinetic Friction)

Coulomb friction (sliding or kinetic friction) has the following characteristics:

a. Resistance is independent of the speed of control motion.

b. It can cause detrimental effects on performance especially if the amount of friction is large in relation to the mass, stiffness, and viscous friction in the system.

c. Some evidence exists which indicates this type of resistance may have beneficial effects in situations involving jolting.

3.1.2.6 Operator Strength and Force Capacity

The maximum amount of force or resistance that can be designed into a control should be determined by the greatest amount of force that can be exerted by the weakest person likely to operate the control. The maximum force that can be applied will depend on such factors as the type of control, the appendage being used to operate the control, the position of the appendage during control operation, the general position of the body, and whether or not support is provided by back rests, etc.

Experimental investigations have provided minimum and maximum amounts of resistance that should be designed into specific controls.+ Listed below are some of the results obtained from experimental studies designed to determine in what direction, from which position, and with what appendage operators can exert the greatest amount of force. The results provide general information useful in the design and location of controls in areas where the operator can exert his maximum amount of strength.

a. For handgrip control operated by the right hand, 90% of a sample population of young men exerted less than 158 lb; the remaining 10%, less than 113 lb. Results obtained for left-hand operation were generally about 10% less.

b. For a seated operator, greater strength could be exerted in a pulling action if the direction of pull was upward from an oblique angle of approximately 45° rather than in a horizontal direction. However, the strength of upward pull was related to the height of the lever grip; a low level (6 in. below seat level) was better than a high level.

c. For a seated operator using his feet for control, greater strength could be obtained in a pushing action if the legs were at an oblique angle rather

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+These are described in the design sections for individual controls. The experimental investigations noted are reported in Chapanis et al.[14]

than if the legs were at right angles to the floor.

d. For three types of control-stick movements (push-pull, turn, and twist) from a prone and seated position, the reliability of force measures was higher for the prone position than for the seated position. The prone position was better for strong pull and turn movements, whereas the seated position was superior for strong push and twist movements. The average maximum force on controls (two-hand operation) for pushing and pulling was 262 lb; for right and left turns, 123 lb; and for right and left twists, 139 lb.

e. For standing operations, the strength that could be exerted was related to the hand position and the required direction of movement. Above the shoulder level, the maximum force was exerted with a downward pulling action. For most hand positions and movement directions below shoulder level, the maximum forces could be exerted at approximately 30 in. below the level of the shoulders.

f. For seated operators exerting force on a rudder-type pedal, the average force exerted (using both legs) was 565 lb; the right leg alone averaged a force of 578 lb; and the left leg, 552 lb. When the right leg alone was used, 200 lb of force could be maintained for 3 min., 38 sec; 500 lb of force for 39. 6 sec; and 600 lb of force for only 20. 1 sec.

g. For seated operators, greater force could be exerted for push-pull movements when the arm was extended straight forward to 30 deg right or left of the forward position. For up-down movements, greater strength could be exerted with the arm more to the side than extended forward.

h. For elbow movements, a bending action (flexion) was stronger than a straightening action (extension), the maximum force being exertable when the elbow was bent at approximately a right angle.

i. For hand-turning actions, the amount of force exertable was related to hand position and turning direction. For turning-in movements, force was greatest when the hand was at a turned-out position, whereas, for turning-out movements, force was greatest when the hand was at a turned-in position.

j. Shoulder actions were generally stronger than elbow actions.

k. In a seated position greater force could be exerted when the operator was required to extend (upward push) rather than flex (downward pull) his shoulder

3.1.3 Coding+

The prime purpose for control coding is to simplify the operator's discrimination processes (i.e., locating and identifying the proper control). The proper application of a control coding system mitigates errors in identification, and reduces the time required to locate the control. In addition, training time for the operator is reduced and positive transfer of training is enhanced when the coding system is standardized for similar equipments.

Situations where coding of controls could be employed include the following:

a. There is a multiplicity of similar controls.

b. Operator vision is restricted.

+ For further reading on the coding of controls see Ely et al[26] and Hunt[45].

c. The space and configuration limitations of a particular workspace necessitate that controls be placed closer to each other than is preferred or that controls be displaced with respect to the operator's immediate area of vision.

The type or types of coding system to be used depend upon the following:

a. Functional nature of the control task and the relative and absolute frequency of the operation.

b. Speed and accuracy with which the control must be identified (performance requirements).

c. Total demands upon the operator at the time that a control must be identified.

d. Extent and types of control coding already being employed in the system.

e. Number of controls to be coded.

f. Space available for locating the controls.

g. Effects of coding upon precision, speed, and ease of manipulation.

h. Illumination of the operator's workplace

i. Cost and availability of special equipment required for coding.

Methods for coding of controls include:

a. Shape.

b. Size.

c. Color.

d. Location.

e. Labeling.

3.1.3.1 Shape Coding

Shape coding can facilitate visual or tactual identification (under conditions of restricted visibility). The ability to discriminate by touch improves substantially with training. When feasible, it is desirable to select functional shapes which suggest the purpose of the control. General guidelines are listed below to aid the design engineers in arriving at suitable methods of coding controls.

* Standardized shapes should be used whenever possible.

* Shapes should be identifiable visually and tactually.

* Sharp edges on the parts of the control which must be grasped should be avoided.

3.1.3.2 Size Coding

Controls may be coded on the basis of size alone, although the number of sizes that can be used is quite limited. The ability to discriminate shape is relatively independent of size; therefore, size coding may be superimposed upon shape coding. General guidelines for size coding of controls include the following:

* When the operator cannot compare the sizes of all controls before selecting the proper one (i.e., absolute discrimination), only two or three different sized controls should be used (viz., small, medium, and large).

* When the operator can visually compare the sizes of all controls before selecting the desired one (i.e., relative discrimination), more than three categories of size coding can be used.

* When coding for size, adequate space should be made available between controls to provide for optimum tactual discrimination and effective manipulation.

* Size of the control knob should be related to the operational torque requirements.

3. 1. 3. 3 Color Coding

There has been very little systematic research on the use of color for coding of controls and little use has been made of this technique. It is not recommended as an effective means of coding controls other than emergency type controls which conventionally are red in color. However, general guidelines are presented below to aid designers contemplating the use of color for control coding.

* Color coding of controls should be used only when vision is unrestricted and when the level of ambient illumination is sufficient to permit cone vision.

* For important and frequently used controls, the color selected should have high spectral visibility in order to attract operator attention and minimize search time.

* Colors selected for critical controls should be in sharp contrast to those selected for noncritical controls.

* Colors used should differ considerably among themselves.

Where practical, colors assigned should have some universally accepted meaning (e. g. , red for emergency-type controls).

3. 1. 3. 4 Location Coding

Coding of controls by location is most effective where blind-positioning movements are required. Listed below are some general guidelines to follow for the placement of controls to be operated by positioning reactions:

* For more accurate location discriminations, controls should be located in the forward area.

* Controls should be located in areas lower than the level of the operator's shoulders.

* When locating controls in the forward area, a separation of 6 to 8 in. is required for optimum discrimination.

* When controls are located to the side or towards the back of the operator, a separation of 12 to 16 in. is necessary for effective operation and accurate discriminations.

3.1.3.5 Labeling Coding[+]

The most frequently used method of making controls unique and distinctive from one another is that of identification by labeling. The problem of labeling controls from the coding standpoint reduces itself to that of presenting legible and meaningful symbols.

3.1.4 Compatibility

Compatibility in control design refers to the natural or expected movement relationship that exists between controls and their function or purpose. Such relationships usually have developed out of conventions that have become accepted practices. There are often "population stereotypes" in the operation of controls that have developed without any sound bases (e.g., a light switch is moved to the "Up" position for "On"). Regardless of how these expected control movements have developed, it is useful to employ this principle of compatibility in the design of controls whenever possible. Its primary effectiveness is in the reduction of reversal errors which occur most frequently under conditions of stress or emergency; this type of human error is attributed to controls designed to operate in a manner contrary to normal movements or habit patterns of the operator.

In some situations, the application of the principle of compatibility requires only a little common sense; in others, an empirical study may

[+]Detailed discussion of labeling will be found in the subsection Markings, page 202 ff.

be necessary to determine what is the natural or preferred pattern to the operator. Listed below are some of the results obtained from such investigations. These should be used as general guidelines in control design.

* Control movements and location should be parallel to the axis of the display motion which they affect.

* When using a rotary control to control a moving pointer on a fixed circular dial, a clockwise rotation of the control should cause a clockwise rotation of the pointer.

* When using a two-position toggle switch or a lever, movement to the right, forward, or up means "On," "Right" or "Forward," "Plus" or "Increase"; movement to the left, down, or back means "Off," "Left or Reverse," "Minus" or "Decrease."

* For groups of controls on panels differing in configuration but reasonably consistent in the control action to be taken (e.g., to increase) it is desirable, when possible, to have consistency in the direction of control operation. (This assumes that all panels are in a vertical plane in front of the operator; it is not applicable for controls located overhead or behind him.)

3.1.5 Accidental Activation

The final factor to consider in the design of controls to minimize human error in their operation is accidental activation. This type of error occurs in work stations where controls are so located that they are susceptible to being moved when the operator reaches for or operates another control or makes normal movements in the vicinity of the equipment. The consequences of inadvertent control operation on system performance undoubtedly vary along a continuum from not serious to grievous. Hence the design engineer, in deciding whether or not to provide a method to prevent this type of human error, must be aware of the implications of accidental control action and must consider the extent

to which other human engineering design features are compromised. For example, a method that protects against accidental activation may increase the time required to operate the control to such an extent as to degrade system performance significantly.

Presented below are several techniques for preventing accidental activation of controls. (Fig. 3-39.)

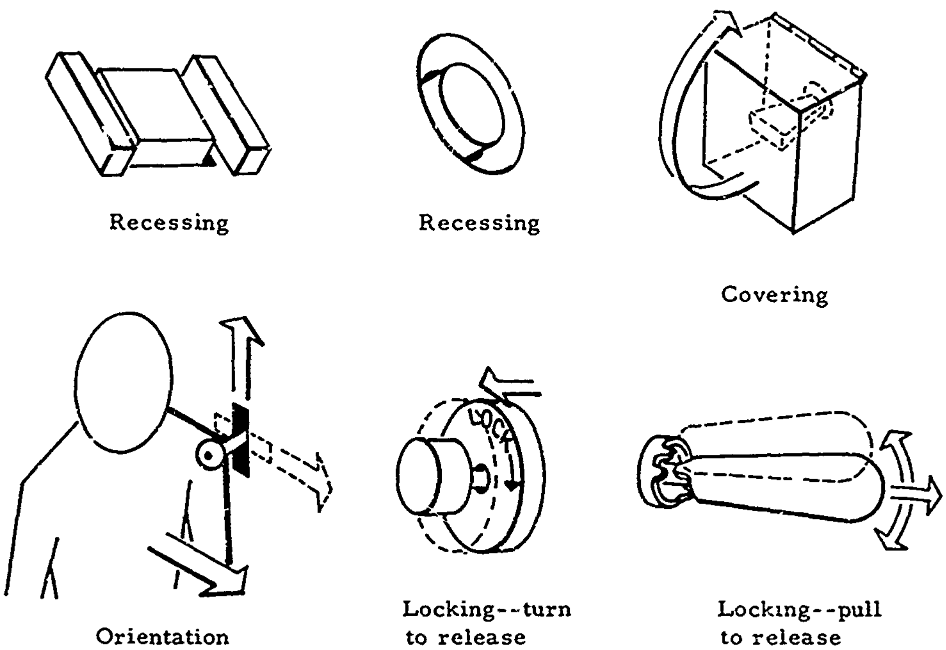


Fig. 3-39. Methods for preve..ion of accidental activation of controls.

3.1.5.1 Recessing

Controls are recessed into the control panel so that they do not protrude. The major disadvantage of this method is the relatively large amount of panel space consumed. A related technique is tha of placing raised barriers around the control under consideration.

3.1.5.2 Location

Controls are so located that they are unlikely to be hit accidentally. One control may be isolated from the others, or controls may be arranged so that the sequence of operations is not conducive to accidental activation of any control.

3.1.5.3 Orientation

The direction of movement of the control is oriented along an axis in which accidental forces are least likely to occur. Particular care should be taken to insure that desirable direction-of-motion relationships are not violated.

3.1.5.4 Covering

Protective covers or guards are placed over each control. If the control under consideration is operated frequently, this method should not be used.

3.1.5.5 Locking

Controls are locked in position. In general, this method requires the sequential application of force in at least two directions before the control operation has any effect. This method is undesirable for frequently operated controls.

3.1.5.6 Operation Sequencing

A series of interlocks prevents Step 2 from being performed before Step 1, Step 3 before Step 2, Step 4 before Step 3, etc.

3.1.5.7 Resistance

The proper type and amount of resistance can effectively reduce the possibility of accidental activation of the control.

3.2 Hand Controls

This section summarizes design guidelines for each of the commonly used controls.[+]

The terms used to describe resistance should be noted For toggle switches, handwheels, cranks, and hand-operated levers, resistance is described in terms of linear resistance (i. e., the resistance at the point where the operator applies force to the control) rather than torque. For these controls, operator output can normally be considered as a force relatively independent of control radius.

For rotary selector switches, continuous-position controls, and finger-operated levers (joysticks), resistance is described in terms of torque. The force which can be brought to bear on the control is a function of the "efficiency" of the operator's grasp (i. e., the amount by which the fingers must be spread or extended) which, in turn, is related to control diameter.

3.2.1 Push Buttons

3.2.1.1 Dimensions

* Minimum diameter

a. Fingertip operation:	1/2 in.
b. Emergency control which can be activated by thumb or heel of hand:	3/4 in.
Maximum diameter	No limitation

3.2.1.2 Displacement

* Minimum:	1/8 in.
Maximum	
a. Nonmatrix operation:	3/4 in.
b. Matrix operation:	1/2 in.

[+]This material is largely from Fly et al.[26]

3.2.1.3 Resistance

* The force required for operation should be as follows:

Minimum

a. Nonmatrix operation: 10 oz.

b. Matrix operation: 5 oz.

Maximum

a. Nonmatrix operation: 40 oz.

b. Matrix operation: 20 oz.

The type of resistance used should be elastic resistance aided by a slight amount of sliding friction, if necessary. It should start low, build up rapidly, and drop suddenly to indicate that the control has been activated. Viscous damping and inertia should be minimized.

3.2.1.4 Coding

* Hand push buttons can be coded by size, location, or labeling. Push buttons used as emergency controls should be red.

3.2.1.5 Accidental Activation

* Accidental activation can be prevented most easily by recessing or covering. Location, operation sequencing, and resistance are other techniques that may be used.

3.2.1.6 Other

* Shape should be concave to fit the finger.

* For areas in which the ambient noise level is low, an audible click should be provided to indicate that the control has been activated.

SECTION 4 DESIGN OF EQUIPMENT FOR MAINTENANCE

* The surface should be provided with a high degree of frictional resistance to prevent slipping.

3.2.2 Toggle Switches

3.2.2.1 Dimensions

* Control tip diameter

a. Minimum: 1/8 in.

b. Maximum: 1/2 in.

* Toggle arm length

a. Minimum: 1/2 in.

b. Maximum: 1 in.

3.2.2.2 Displacement

* Minimum (between adjacent control positions)

a. Two-position: 40 deg

b. Three-position: 20 deg

Maximum (between adjacent control positions)

a. Two-position: 60 deg

b. Three-position: 30 deg

3.2.2.3 Resistance

* The force required for operation should be as follows:

a. Minimum: 10 oz.

b. Maximum: 40 oz.

The type of resistance used should be elastic resistance which builds up, then decreases as the desired position is approached so that the control will snap into its position and cannot stop between adjacent positions. Friction and inertia should be minimized.

3.2.2.4 Coding

* Toggle switches can be coded by location or labeling. Toggle switches used as emergency controls should be red.

3.2.2.5 Accidental Activation

* Accidental activation can be prevented by using any of the methods (i.e., recessing, location, orientation, covering, operation sequencing, resistance, and pull-to-unlock mechanisms).

3.2.2.6 Other

* Toggle switches should be vertically oriented with the "Up" position for "On" and "Down" position for "Off." (Toggle switches should be mounted for horizontal operation only if it is necessary to be consistent with the orientation of the controlled function or equipment location, or to prevent accidental activation of the wrong switch.)

* For areas in which the ambient noise level is low, an audible click should be provided to indicate that the control has been activated.

* For areas where drip-proof components are required, switches with toggle bushing seals should be used. +

3.2.3 Rotary Selector Switches (Bar-Shaped Controls)

There are two major types of rotary selector switches--a moving pointer with a fixed scale and a fixed pointer with a moving scale. For the FBM equipment, it is recommended that only the former be used, i.e., a

+ Sealed toggle bushings are preferred to nonsealed bushings, since rubber toggle-bat covers do not permit a visual cue of switch position.

moving pointer with a fixed scale. The pointer of the rotary selector switch will normally be bar-shaped with a tapered tip, or a line will be inscribed through the center and along the length of the bar to serve as a pointer toward the selected control position.[+]

The guidelines to follow are for the bar-shaped control (hereinafter referred to as pointer) for rotary selector switches having a fixed scale and a moving pointer.

3.2.3.1 Pointer Dimensions

* Length
  - a. Minimum: 3/4 in.
  - b. Maximum: No limitation
* Width
  - a. Minimum: 1/2 in.
  - b. Maximum: 1 in.
* Depth
  - a. Minimum: 1/2 in.
  - b. Maximum: 4 in.

3.2.3.2 Displacement (between adjacent detents)

* Minimum
  - a. For visual positioning: 15 deg
  - b. For nonvisual positioning: 30 deg

[+] Figure 3-21 illustrates the bar-shaped knob.

Maximum

a.	For visual positioning:	40 deg
b.	For nonvisual positioning:	40 deg

3.2.3.3 Resistance

* The torque required for operation should be as follows:

a.	Minimum:	1 in.-lb
b.	Maximum:[+]	6 in.-lb

* Detents should be provided at each control position (not including momentary contact positions). The type of resistance used should be elastic resistance which builds up, then decreases as each detent is approached so that the control will snap into position without stopping between adjacent positions.

3.2.3.4 Coding

* Rotary selector switches may be coded by location or labeling.

3.2.3.5 Accidental Activation

* Accidental activation can be prevented by location, operation sequencing, and resistance.

3.2.3.6 Other

* A bar-shaped knob with parallel sides should be used on rotary selector switches. The index side should taper to a point.

[+] Switchboard selector switches which require more than 6 in.-lb torque for operation should use a larger hand grasp type of control.

* Rotary selector switches should have a fixed scale with a movable pointer.

* It is undesirable for a rotary selector switch to have more than twenty-four positions. However, when more positions must be made available, a minimum separation of 1/4 in. between settings should be maintained.

* Whenever possible, switch positions should be located within an arc of less than 180 deg in order to reduce setting and reading errors.

* Stops should be placed at the beginning and end of the range of control positions. This will facilitate blind positioning by enabling the operator to count the number of settings (by the feel of the detent action or by the sound of the click) from a starting position.

* For areas in which the ambient noise level is low, an audible click should be provided to indicate control activation or change in switch position.

* Setting value should increase with clockwise movements.

* Scale should be visible when the operator's fingers are on the knob.

* Pointer end of the knob should be close to the scale index mark to minimize parallax.

* Grasp area should be either serrated or provided with a high degree of frictional resistance to prevent slipping.

* Ganged selector switches should be used only when space is limited.

3.2.4 Rotary Selector Switches (Thumbwheel Controls)

Thumbwheel controls may be preferred[†] if the function requires a compact digital or binary control-output device (for a series of numbers) and, in addition, a readout of these manual inputs for verification (shown in Figure 3-21). Detent indexing units should provide 10-position (0-9) digital or binary (3- or 4-bit and complement) output.

3.2.4.1 Thumbwheel Dimensions

* Wheel diameter
  - a. Minimum: 1-1/2 in.
  - b. Maximum: 2-1/2 in.
* Width
  - a. Minimum: 1/4 in.
  - b. Maximum: 1/2 in.
* Depth
  - a. Minimum: 1-1/2 in.
  - b. Maximum: 4 in.

3.2.4.2 Displacement (between adjacent detents)

* Set by number of positions (i.e., 36 deg for 10 positions).

3.2.4.3 Resistance

* The torque required for operation should be as follows:
  - a. Minimum: 1 in.-lb
  - b. Maximum: 3 in.-lb

[†]For FBM applications where the drip-proofing requirements can be waived (e.g., for thumbwheels mounted in an enclosure).

* Detents should be provided. The type of resistance used should be elastic resistance which builds up, then decreases as each detent is approached so that the control will snap into position without stopping between adjacent positions.

3.2.4.4 Coding

* Thumbwheel controls may be coded by location, labeling, and color (e.g., use of reverse color for least significant digit wheel, similar to odometer coding).

3.2.4.5 Accidental Activation

* Accidental activation can be prevented by recessing, covering, location, operation sequencing, and resistance.

3.2.4.6 Other

* Setting value should increase with downward stroke on the thumbwheel.

* A portion of adjacent numbers should be visible to indicate direction of increase or decrease.

* For areas in which ambient illumination is low (below 1 ftL display brightness), the thumbwheel should be internally illuminated. Digits should appear as illuminated characters on a black background and dimensions should approximate the following: character height, 1/4in.; height-to-width ratio, 3:2; height-to-strokewidth ratio, 10:1.

* For areas where display brightness, due to ample ambient illumination, is expected to be above 1 ftL, the internal illumination provision is not required. Digits should be engraved and filled with black and should appear on a light

(or white) thumbwheel. Character dimensions should approximate those given for illuminated characters, except for strokewidth-to-height ratio, which should be 5:1 (bold black characters).

* Thumbwheel design should permit side viewing of in-line digital readout (from both sides) from offset operator positions which are nearly parallel with respect to the panel (viz., the raised control area should not interfere with the display).

* Each position around the circumference of the wheel should have a slightly concave surface on which the number is located. Each position should be separated by a serrated (or high-friction) area which may be raised no greater than 1/16 in. from the periphery of the thumbwheel.

3.2.5 Continuous Position Controls

3.2.5.1 Dimensions

Within the ranges recommended below, control knob size is relatively unimportant provided the C/D ratio is optimum, the resistance low, and the knob easily grasped. When panel space is limited, the use of minimum values for knob size will not degrade performance provided the resistance is very low. (Knobs should be pointer-shaped when control position is important.)

* Depth
  - a. Minimum: 1/2 in.
  - b. Maximum: 1 in.

* Diameter
  - a. Minimum: 3/8 in.
  - b. Maximum: 4 in.

When resistance is very low, knobs may be miniaturized. In this case the minimum depth should probably remain 1/2 in., but the minimum diameter can be reduced to as little as 1/4 in.

3.2.5.2 Displacement

* Displacement should be determined by the desired C/D ratio.

3.2.5.3 Resistance

* The torque required for operation should be as follows:

  a. Minimum: No limitation

  b. Maximum:

     (1) For operation with small (less than 1-in. diameter) knobs: 4-1/2 in.-oz.

     (2) For operation with large (above 1-in. diameter) knobs: 6 in.-oz.

The type of resistance used for a particular knob depends upon performance requirements. Reports to date indicate that, for maximum accuracy when direct positioning is required, dry friction should be zero and the torque required to overcome inertia should be the maximum that the physical capabilities of the operator will permit.

3.2.5.4 Coding

* Knobs can be coded by any of the methods listed for coding of controls; however, they lend themselves especially well to shape coding.

3.2.5.5 Accidental Activation

* Accidental activation can be prevented most easily by location. Other techniques such as recessing, covering, and resistance can also be used.

3.2.5.6 Other

* Small knobs (less than 3/4 in.) should be knurled and large knobs (more than 3/4 in.) serrated to prevent slipping.

* Scale should be visible when the operator's fingers are on the knob.

* Setting value should be increased by clockwise rotation.

* If a pointer or index is used on the control, it should be close to the scale index mark to minimize parallax.

* When bracketing is used for locating a visual or auditory null position (e.g., tuning a transmitter), the knob should move through an arc of 10 to 20 deg on either side of the null position before a misalignment is noticeable.

* Knob diameter should increase with increases in the amount of torque required for control operation.

3.2.6 Handwheels

3.2.6.1 Dimensions

Handwheels are normally designed for two-hand operation. (Rotary controls small enough to be grasped by one hand are classified as continuous position controls and have been discussed previously.)

* Handwheel diameter

a. Minimum: 7 in.

b. Maximum:

(1) Seated operator with hands at each end of the diameter (most desirable position for making precise setting): 21 in.

(2) Operator does not have to hold handwheel at opposite ends of its diameter: No limitation

* Cross-sectional rim diameter

a. Minimum: 3/4 in.

b. Maximum: 2 in.

3.2.6.2 Displacement

Displacement should be determined by the desired C/D ratio.

* When the handwheel moves through a large arc, the C/D ratio can be increased either by increasing the number of control rotations per unit movement of the controlled object or by increasing handwheel diameter.

* When the handwheel movement is limited to small arcs, the C/D ratio can be increased by increasing the handwheel diameter. In such situations, control movements are nearly linear; hence, increasing the extent of control movement will increase the C/D ratio even though the arc of rotation (as measured in angular units) is not increased.

3.2.6.3 Resistance

The type of resistance to be used depends primarily on performance requirements. For controls moving through small arcs, inertia should be minimized. For handwheels which are set at either of two limits of travel, inertia should be maximized.

3.2.6.4 Coding

* Handwheels can be coded by ə, location, and labeling. (Handwheels d as emergency controls should be red.)

3.2.6.5 Accidental Activation

* The accidental activation of handwheels is most easily prevented by locking the handwheel in place with a pin. All important handwheels in the ship subsystem should be provided with a locking feature. Accidental activation may also be prevented by the techniques of location and resistance.

3.2.6.6 Other

* When large displacements (greater than 120 deg) must be made rapidly, a crank or spinner handle may be attached to the handwheel

* If the handwheel interferes with vision, only the two sections the operator must grasp should be provided. These sections are usually the chords of arcs, each approximately 6 in. long, across from one another. However, if multiple rotation is required, the entire handwheel should be retained.

* The gripping surface should be indented or knurled as an aid in grasping and turning the handwheel.

3.2.7 Handcranks

The sizes of handcranks are discussed in terms of their radius. The radius refers to the distance from the crank handle to the center of rotation.

3.2.7.1 <u>Dimensions</u>

* Radius

a. Minimum: 1/2 in.

b. Maximum:

(1) Heavy load: 20 in.

(2) Minimum load and very high rate (up to 275 rpm): 4-1/2 in.

* Under no-load conditions, small cranks can be turned more rapidly than large ones. However, as the load increases, the crank size which maximizes turning rate also increases. For rotating a crank at a constant rate, larger cranks (4-1/2 in. radius or greater) are better than smaller ones.

3.2.7.2 <u>Displacement</u>

Displacement is determined by the desired C/D ratio.

3.2.7.3 <u>Resistance</u>

The resistance of handcranks should be measured as a linear force which is applied at a point on the crank handle.

* The force required for operation should be as follows:

a. Small cranks (less than 3-1/2 in. radius)

(1) High-speed operation (rapid, steady turning)

(a) Minimum: 2 lb

(b) Maximum: 5 lb

b. Large cranks (5 to 8 in. radius)

(1) High-speed operation (rapid, steady turning)

(a) Minimum: 5 lb

(b) Maximum: 10 lb

(2) Making precise settings (adjusting between 1/2 to 1 rotation)

(a) Minimum: 2-1/2 lb

(b) Maximum: 8 lb

The type of resistance to be used depends on performance requirements.

* The following points should be noted:

a. In general, any amount of resistance will decrease the turning rate (maximum turning rate of 275 rpm achieved with a handcrank having a radius of 3 to 4 cms).

b. Friction (2 to 5 lb) reduces the effects of jolting.

c. Friction degrades performance in rotating a crank handle at a constant rate: primarily at low rates (3 to 10 rpm), slightly at moderate rates (about 30 rpm), negligibly at high rates (above 100 rpm).

d. When a crank handle is rotated at a constant rate, inertia aids performance, particularly for small cranks and at low rates.

3.2.7.4 Coding

* Cranks can be coded by location or labeling. (Cranks used as emergency controls should be red.)

3.2.7.5 Accidental Activation

* Accidental activation can be prevented by locking, location, and resistance techniques.

3.2.7.6 Other

* A crank handle should be designed to turn freely around its shaft.

* Contact surface should be provided with a high degree of frictional resistance to prevent slipping.

* As the load increases, crank size should also increase to maintain turning rate.

* Cranks should be positioned with respect to the speed or load they administer, i.e., small cranks with light loads should be positioned at elbow height for fast wrist action; large cranks with heavier loads should be oriented for full arm motion.

3.2.8 Levers

3.2.8.1 Dimensions

* The length of the lever should be determined by the function it is to serve in a specific situation and the mechanical advantage required. However, when using a lever in a positioning task, it has been found that, in terms of accuracy, the length of the lever is of relatively little importance provided the optimum C/D ratio (3:1) is maintained

3.2.8.2 Displacement

* The amount of displacement required should be determined by the position of the lever in relation to the operator, the position of the operator (seated or standing), and the degree of free movement for the operator.

3.2.8.3 Resistance

The resistance of levers should be measured as a linear force which is applied at a point on the lever handle.

* The force required for the operation should be as follows:

a. Minimum:

(1) Lever handle grasped by finger: 12 oz

(2) Lever handle grasped by hand: 2 lb

b. Maximum:

(1) Lever handle grasped by finger: 32 oz

(2) Lever handle grasped by:

(a) one hand (push-pull): 30 lb

(b) two hands (push pull): 90 lb

(c) one hand (right-left): 20 lb

(d) two hands (right-left): 30 lb

The type of resistance used for levers is primarily elastic resistance. Elastic resistance which increases nonlinearly may be used for joysticks to improve "stick feel" for the operator.

3.2.8.4 Coding

* Levers can be coded by labeling and location. The handles of levers also can be shape coded. (Levers used as emergency controls should have red handles.)

3.2.8.5 Accidental Activation

* Accidental activation can be prevented by locking, orientation, location, or resistance techniques.

3.2.8.6 Other

* In making fine adjustments with small levers (e.g., joysticks), support should be provided for the body part being used as follows:

  a. Elbow support for large hand movements.

  b. Forearm support for small hand movements.

  c. Wrist support for fine movements.

In making very fine adjustments with a small joystick, operators often rest their wrist on the control panel and grasp the control pencil-style below the tip rather than on it. In such situations, the pivot point should be recessed below the surface on which the wrist rests.

* Dead space should be provided at the neutral positions for joysticks. Detents should not be provided with joysticks.

* Contact surface should be provided with a high degree of frictional resistance to prevent slipping.

* When levers are associated with displays, the tip of the lever should move between 2-1/2 and 3 times as fast as the displayed function.

* Displacement of the lever arm should not exceed the convenient arm reach of the operator or move through an arc greater than 90 deg in any direction.

* Where large displacements are required, a long lever arm should be used in order to retain a linear handle motion.

3.3 Foot Controls

3.3.1 Foot Push Buttons

3.3.1.1 Dimensions

* Minimum: 1/2 in.

Maximum: No limitation

3.3.1.2 Displacement

* Minimum: 1/2 in.

Maximum:

a. Operation by ankle flexion only: 2-1/2 in.

b. Operation by leg movements: 4 in.

3.3.1.3 Resistance

* The force required for operation should be as follows:

Minimum:

a. Foot will not rest on the control: 4 lb

b. Foot may rest on the control: 10 lb

Maximum:

Normal operation with foot resting or not resting on control: 20 lb

The type of resistance used should be elastic resistance, aided by static friction to support the foot. Resistance should start low, build up rapidly, then drop suddenly.

3.3.1.4 Coding

* Foot push buttons can be coded only by location.

3.3.1.5 Accidental Activation

* Accidental activation can be prevented by location, operation sequencing, and resistance techniques.

3.3.1.6 Other

* Controls should normally be designed for toe operation (by the ball of the foot) rather than heel operation. Where space permits, push buttons should be replaced by a pedal hinged at the heel. This device serves to aid the operator in locating and activating the control.

* For areas in which the ambient noise level is low, an audible click should be provided to indicate that the control has been activated.

* Contact surface should be provided with a high degree of frictional resistance to prevent slipping.

3.3.2 Pedals

3.3.2.1 Dimensions

* Minimum: 1 x 3 in.

* Maximum: Consider space available plus danger of accidental activation. Desirable to have pedal sufficiently large to accommodate entire foot.

3.3.2.2 Displacement

* Minimum:

a. Normal operation: 1/2 in.

b. Wearing heavy boots: 1 in.

* Maximum:

a. Ankle flexion only: 2-1/2 in.

b. Leg movement: 7 in.

3.3.2.3 Resistance

* The force required for operation should be as follows:

Minimum:

a. Foot will not rest on the control: 4 lb

b. Foot may rest on the control: 10 lb

Maximum:

a. Ankle flexion only: 20 lb

b. Leg movement: 180 lb

The type of resistance used should prevent forces less than those required for breakout from accidentally activating the control. Elastic resistance should be provided to allow the pedal to return to a neutral position following removal of the operating force.

3.3.2.4 Coding

* Pedals can be coded only by location.

3.3.2.5 Accidental Activation

* Accidental activation can be prevented by location and resistance techniques.

3.3.2.6 Other

* Foot pedals as control devices should be used when a large amount of force and displacement is required.

* Pedals should be covered with a nonskid material.

* Pedals should be pivoted so that the control action is similar to the limb or foot motion, i.e., near the heel for ankle motion (e.g., accelerator pedal) and above the foot for leg motion (e.g., brake pedal).

III. INTERIOR COMMUNICATION EQUIPMENT

1. Description

Any communication system includes essentially four elements: (1) the message to be transmitted; (2) the display (a sound signal, a voice, etc.); (3) the transmission system (the air, a telephone system, etc.); and (4) the receiver (usually an individual).

1.1 Methods of Communication

The transmission of information within the submarine, either verbally or by other means, can be classified as follows:

	Transmission+	Reception
a.	Voice	Ear
b.	Voice to microphone	Speaker to ear
c.	Voice to telephone	Telephone to ear
d.	Voice to recorder	Recorder to ear
e.	Switch to closure	Auditory display (buzzer, bell)
f.	Switch closure	Visual display (light, CRT)
g.	Written message	Read message

1.2 Classification of Communication Equipments

1.2.1 Exterior Communications

These include radio and/or other methods of intership or ship-to-shore communication. (These types of communication systems will not be discussed in this handbook.)

1.2.2 Interior Communications

According to Section S65, General Specifications for Ships of the United States Navy,(73) interior or intraship communications group into five types of systems.

+This subsection is concerned with oral communications (the first three of the types of communication); the others are discussed under Design of Displays.

1.2.2.1 Telephone Systems

Naval vessels may have two types of telephone systems: electrically powered dial systems (circuit J), and several sound-powered systems.(79) The latter are used extensively aboard naval vessels. In these telephones, the microphones are primarily generators of electrical energy, sound being the only source of input power. The receiving units are capable of receiving energy generated by the microphone and converting the received energy into sound with reasonable fidelity. In general, sound-powered phones have a bandpass from 500 to 2,500 cps.

These systems are available with handsets, head-chest sets, and headset-microphone speaker-receiver combinations.

1.2.2.2 Announcing and Recording Systems

Announcing systems generally consist of announcing equipment and intercommunication units. Shipboard announcing equipment permits the broadcast of speech from a central station to loudspeakers distributed throughout the ship. The typical ship's announcing system consists of microphone, distribution amplifier, appropriate switching equipment, local amplifiers where necessary, and loudspeakers. In addition to speech, certain auditory signals and alarms may be transmitted (e. g. , GQ signal) via the announcing equipment.

Intercoms operate from ship's power and hence permit greater frequency response and acoustical output than sound-powered phones. Speech may be picked up from distances of several feet, transmitted to one or several stations, and broadcast via a loudspeaker. The frequency response of a typical intercom is 300 to 3,000 cps.

1.2.2.3 Voice Tubes

Voice tubes for direct vocal interspace communications are present in FBM submarines, but not as part of the FBM system.

1.2.2.4 Electrical Alarm, Safety, and Warning Systems

This group includes both visual and auditory signaling systems. They are manually or automatically actuated by switch closures and transmitted with other signals on various displays and panels or transmitted as buzzers, horns, claxons, bells, etc. , which may be transmitted via the announcing system.

1.2.2.5 Electrical Indicating, Ordering, and Metering Systems

This group involves the same types of equipment as described immediately above.

2. Selection and Utilization

2.1 General

2.1.1 Requirements for Speech Communication

Communications systems may be affected by ambient noise (surrounding noise) and by system noise (noise in the transmission system itself).

2.1.1.1 Speech Interference Level

The speech interference level (SIL) describes the effectiveness of noise in masking speech. It is defined as the average, in db, of the sound levels of the masking noise in the three octave bands of 600 to 1,200, 1,200 to 2,400, and 2,400 to 4,800 cps. It cannot be used if the masking noise

Table 3-14

Effect of Noise on Voice Communication

SIL (in db)	Distance (ft)	Voice Level	Nature of Possible Communication
45	10	Normal voice	Relaxed conversation
55	3	Normal voice	Continuous communication in work areas
	6	Raised voice	
	12	Very loud voice	
65	2	Raised voice	Intermittent communication
	4	Very loud voice	
	8	Shouting	
75	1	Very loud voice	Minimal communication (danger signals, restricted prearranged vocabulary desired)
	2-3	Shouting	

contains intense low-frequency components or if the noise is concentrated in a narrow band. The effect of noise on voice communication is shown in Table 3-14.

2.1.1.2 Effects of Reverberation on Speech

Reverberation is the effect of noise bouncing back and forth from the walls, ceiling, and floor of an enclosed room. As is known from experience in some rooms or auditoriums, this reverberation seems to obliterate speech or important segments of it. Fig. 3-40 shows approximately the reduction in intelligibility that is caused by varying degrees of reverberation (specifically, the time in seconds that it takes the noise to subside). This relationship essentially is one of a straight line.

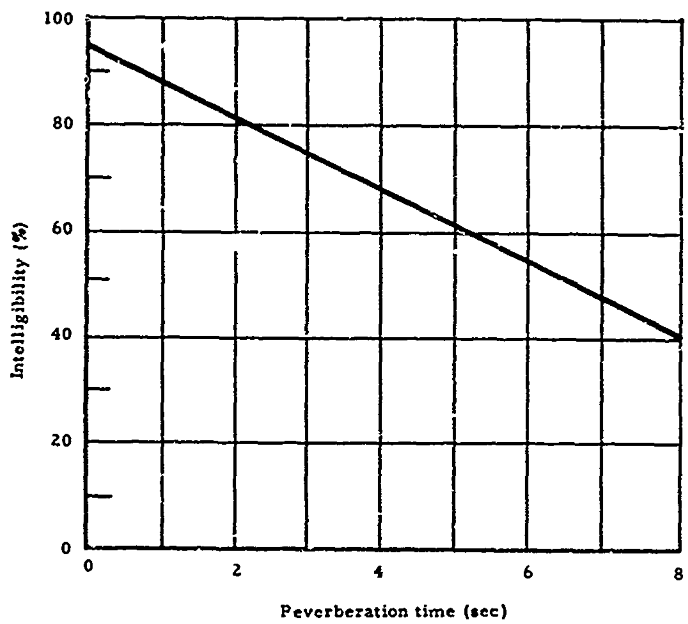


Fig. 3-40. Intelligibility of speech in relationship to reverberation.[30]

2.1.1.3 Intelligibility of Speech

Most communication systems do not transmit speech with high fidelity. Intelligibility, however, does not depend upon hearing each and every speech sound. The elimination of frequencies above 4,000 or 5,000 cps or below 300 or 500 cps has little effect on intelligibility.

2.1.1.4 Effects of Earplugs on Speech

For reduction of possible hearing loss or discomfort, earplugs may sometimes be used. Contrary to what might be expected, the use of earplugs does not always make speech less intelligible, but may actually make it more intelligible. This is particularly true in the case of high noise levels. In the case of low noise levels, the use of earplugs may impair speech intelligibility somewhat.

In high noise level situations, there is a greater likelihood that earplugs will be worn. The explanation for this lies in the fact that, at high noise levels, a point is reached where additional intensity cannot be discriminated. At such levels, the difference between the intensity of the signal (in this case speech) and of its background noise likewise cannot be discriminated. The effect of earplugs under such circumstances is to bring the level of both the signal and the background noise down to the point where the difference between them can be discriminated.

2.1.2 Arrangement of Interior Communication Equipment+

In an area served, audible equipment should be located to insure the maximum audibility. Where more than one audible equipment is present in a space, each should have a distinct tone.

*++ Equipment which requires servicing in its mounted position should be located so that adequate accessibility is provided.

* When voice messages from several sources overlap:

+Section S65-O-c, Specifications for Building Submarines, SSB(N) 616 Class(73).

++The * symbol indicates sections which contain specific guidelines for the selection and utilization of interior communication equipment.

a. Each of the sources (loudspeakers) should be separated by more than 10 deg in the horizontal plane, measured from the listener.

b. Filters should be placed in the most-used circuits so that the aural frequency spectra do not overlap more than is necessary to produce intelligible speech.

c. Indicator lights should be used to show the channel calling when identification is a major problem.

d. Pulldown facilities (switching to a local speaker) should be provided for optional use by the operator.

2.1.3 Effects of Noise on Communication

* At low ambient noise levels, telephone and announcing systems are equally useful. However, as the noise level increases, the usefulness of speakers drops off more rapidly than does that of telephones Increasing the volume of speakers in higher levels of ambient noise also increases the system noise. The resultant signal-to-noise ratio may not be sufficient to maintain the intelligibility of the message.

* Where speech must be carried out under adverse noise conditions, there are certain procedures that can aid in communication:

  a. Use of speech that will most likely "get through," such as the phonetic alphabet used in aviation and by the military services.

  b. Selection and training of good talkers.

  c. Selection of good listeners (receivers).

2.2 Telephone

* A telephone should be used when:

  a. Ambient noise and SIL are too high for an announcing system.

b. Messages are from one person to one person.

* The following telephone equipment should be used:

a. A handset if the operator is in a fixed position and his hands are free.

b. A headset if the operator's hands must be occupied.

c. A headset and long extension cord if the operator must be mobile within a limited area.

2.3 Announcing System and/or Intercom

* An announcing system and/or intercom should be used:

a. In low level ambient noise.

b. When it is desirable to transmit to several stations simultaneously.

c. When it is desirable for several persons within a space to receive together.

d. When a person moving about within a space must receive.

2.4 Major and Minor Sound-Powered Circuits

* At each station having more than one sound-powered telephone circuit, one circuit should be designated as the major means of sound-powered communication.

This circuit may be an open line, in which case the operator must wear earphones in order to receive any message over the circuit at any time; or it may be a call station at which a handset may be used. In the latter case the circuit should also have a ringer circuit by which the operator may be called. The major circuit for a given station may be changed as needed. Thus during watch conditions one circuit may be "major" at a given station: during GQ missile conditions a different circuit may at the same time be the major one. The operator may listen and talk on his major sound-powered circuit only, but may change to a minor circuit as needed by use of a selector switch or jackbox arrangement.

2.5 Talkers

Supervisory personnel may at times be required to maintain communications on or monitor more than one circuit at the same time. Such personnel should be provided with a talker to monitor and repeat messages on the major or the more important circuit.

The duties of the talker are to pass on outgoing messages and to report incoming ones to his principal.

* A talker should be provided for a supervisor or equipment operator who:

    a. Is likely to receive a number of messages arriving on different channels, or

    b. Is likely to receive so many telephone messages on a single channel as to distract him from his task, or

    c. Must move about in a space to the extent that an extension between him and a fixed jackbox or switchbox is impractical.

2.6 Recorded Signals and Directions

* If a large number of events must be designated by auditory signals, or the response to an auditory signal must be complex, a recorded verbal message may be used either solely or immediately following an attention-getting warning. Speech has an inherent advantage in that little or no training is required for its recognition. To prevent confusion, the verbal message must be unequivocal and must be repeated enough times to insure that the message is understood.

3. Design

3.1 General

*+ Satisfactory speech communication requires:

+The * symbol indicates specific guidelines for the design of interior communication equipment.

a. Reproduction of the audio frequency range between 200 and 6, 000 cps for satisfactory intelligibility and expression.

b. Audio signal power of approximately 300 milliwatts at the ear.

c. Signal-to-noise ratio of at least 5:1.

d. Signal free from distortions and masking effects attributable to nonuniform frequency response or to the lack of uniform amplification.

3.2 Receiver and Headset

* The receiver and headset should have the following characteristics:

a. Gain control with dynamic range sufficient to make the signal 15 db more intense than the noise.

b. Reduction in frequency range below 500 cps and above 4, 000 cps, if it results in an increase of the average power of the audio signal.

c. Uniform frequency response between 300 and 3, 000 cps to avoid distortion.

IV. PANELS AND CONSOLES

1. Description

The control and display panels and consoles which are used in the FBM system are, for the most part, of the conventional metal type. However, special light-conducting panels are used in workplaces where the operator is required to perform his tasks under low-level illumination. Moreover, new techniques of panel construction are being developed, such as the mated front panel and subpanel assemblies (e. g., the Mark 84 Fire Control Console), and may be expected to be used more on future equipments.

1.1 Metal Panels

The conventional metal panel is mounted on a structural framework and serves both as the outer covering for the equipment and as a mounting structure for displays, controls, and other components. (Figure 3-41.) The components are usually fastened to the panel by means of screws or spring clips. The modularization of components when mounted on conventional metal panels is limited because of the amount of space required for mounting and the problem of providing a strong supporting structure.

The illumination of conventional metal panels usually is provided by general or supplementary luminaires arranged throughout the workplace to provide a reasonably uniform distribution of light over the entire control and display surface. When necessary, illumination is provided by internal self-contained lighting in the components (e. g., indicator lights, internally illuminated meters, etc.).

1.2 Light-Conducting Panel Construction

The use of special light conducting panels provides internal illumination for ease of viewing under conditions of low ambient illumination (e. g., low-level (red) lighting used in some ship control compartments). These panels have been classified as Types I, II, and III. Types I and II consist of a single panel using edge-lighting techniques. Type III represents a refinement of the first two types and uses a duo-panel plastic light conducting system. This consists of a thin plastic indicia panel which covers, but is not in substantial optical contact with, a light conducting panel. The

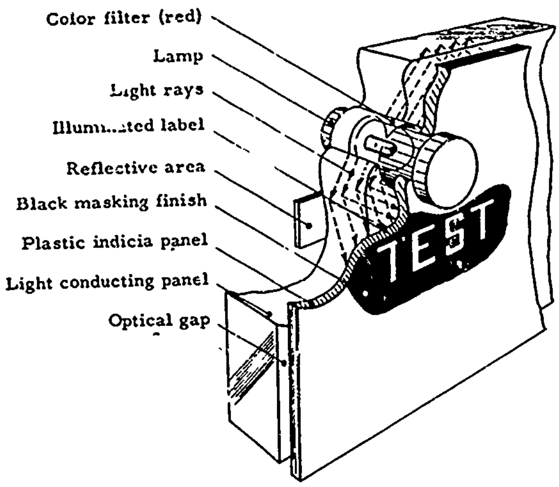


Fig. 3-42.
Light conducting panel

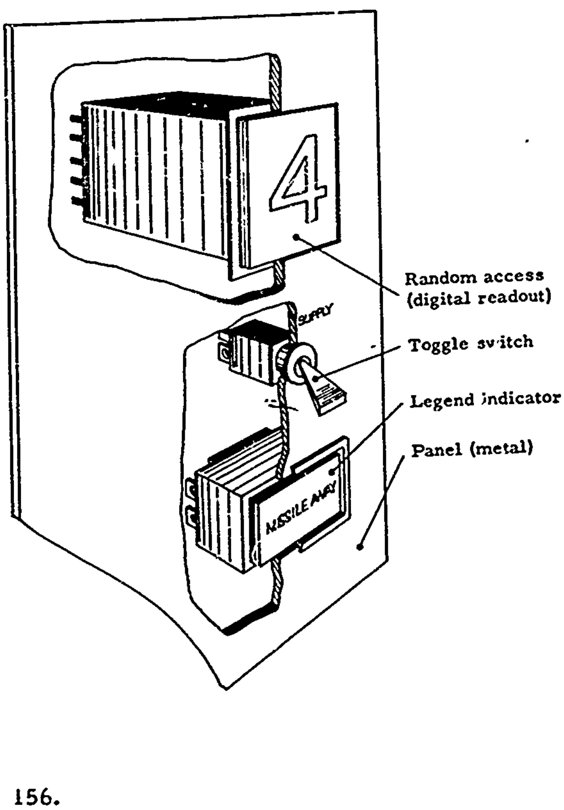


Fig. 3-41.
Conventional metal panel

light conducting panel is selectively painted on one surface and edges to reflect light conducted within the panel out through translucent markings on the indicia panel. (Fig. 3-42.)

1.3 Mated Front Panel and Subpanel Assemblies

The mated front panel and subpanel assemblies (such as the Mark 84 Fire Control Subsystem technique) utilize a "building block" concept. The structure on which the panels are mounted is designated as a Type 1 module. The Type 2 module consists of a plate (which contains wire-wrap posts on one side and female receptacles on the other side for plugging in Type 3 component modules), interconnecting wiring and clamps for fastening the assembly to the Type 1 structure. (Fig. 3-43.)

The Type 3 modules, which are the control and display components and other associated electronics, contain the majority of the functional circuits utilized in the equipment; e.g., printed circuit boards, test points, connector header (containing a standard array of blade-type contacts), hold-down screws, and a keying technique to insure insertion of the Type 3 module in the proper place on the Type 2 module. These modules are available in 20, 30, and 40 contact sizes, and include digital, analog, cable connector, relay holder, display, and switch modules. The illuminated display lights are referred to as the "short" units and the illuminated switch-display modules are referred to as the "long" units. The short units provide up to three colors with two lamps for each color and are 1.2 in. x 1.2 in. x 1.740 in. (max.) long. The long units also provide up to three colors and six lamps together with a push-button switch capability and are 1.2 in. x 1.2 x 3.875 in. long. These units are available with a variety of connectors including one for use with Type 2 modules, solder connections, and screw fasteners. Most of the control and display components can be mounted on a conventional metal panel as well as on subpanels.

The front panel consists of fiberglas and serves as a cover plate with selective translucent display areas and cutouts for controls. These are indexed for proper alignment with the subpanel-mounted components. The components are accessible for maintenance from the front of the equipment by means of a hinged assembly that allows the fiberglas panel to swing open.

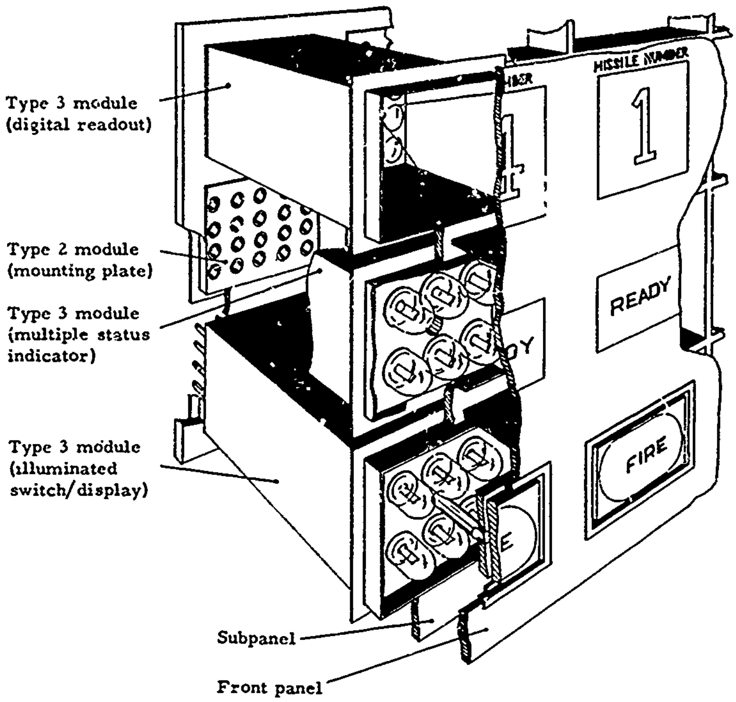


Fig. 3-43. Mated panel.

2. Measurements of Personnel

The design of any control and display panel or console, or any workplace, requires consideration of the physical dimensions of the human body. The measurements which quantitatively describe the exterior dimensions of the human body are commonly referred to as anthropometric data.

Anthropometric data have been obtained on large samples of the population in the military services. These data are usually expressed in terms of percentiles. The 5th, 50th, and 95th percentiles are most commonly used and are provided in this handbook. The range from the 5th to the 95th percentile encompasses 90% of the population on which the measures were obtained. Thus, a measure at the 5th percentile would mean that, of the total number of people measured, 95% exceeded that measure and 5% were below it. The median, or midpoint, would be the 50th percentile, which is interpreted as 50% exceeding the measure and 50% below.

*+ The measurements of the human body which should be used in the design of control and display panels and consoles are summarized in Figure 3-44.

The measures which are presented in Figure 3-44 are considered representative of the adult male population entering submarine service since Navy medical regulations do not impose any specific restrictions on the physical dimensions of personnel and the data in this figure are based on large samples of personnel in the military services.(77)

The data in Figure 3-44 require some explanation in order that they will be applied most effectively for design situations not covered in the subsections on visual and manual workplaces.

* When designing for personnel size, the designer should:

a. Use the 95th percentile for all situations where physical clearance is involved (e.g., seats, access space, aisle width, knee clearance, etc.) The requirement here is to accommodate the largest personnel expected to operate the equipment.

b. Use the 5th percentile for all situations where physical proximity is involved (e.g., reaching controls). The requirement here is to accommodate the smallest personnel.

+ The * symbol indicates specific guidelines for the application of the information on measurements of personnel

Measurements of Personnel (in.)

Ref. No.	Measure	5th Percentile	50th Percentile	95th Percentile
1	Hand breadth	3.2	3.5	3.7
2	Hand length	7.0	7.6	8.2
3	Forward reach, from wall	31.9	34.6	37.3
4	Abdominal depth	7.9	9.0	10.5
5	Buttock depth	7.5	8.8	10.4
6	Knuckle height	28.[illegible]	31.1	33.5
7	Elbow height	41.7	44.6	47.5
8	Shoulder height	53.[illegible]	57.7	61.3
9	Eye height, standing	61.9	65.8	69.7
10	Standing height	66.3	70.3	74.4
11	Vertical reach	77.0	83.6	90.3
12	Arm span, total	65.9	70.8	75.6
13	Chest breadth	10.7	12.0	13.4
14	Hip breadth, standing	11.9	13.2	14.7
15	Foot breadth	3.9	4.2	4.5
16	Sitting height (from floor)	49.1	52.6	56.2
17	Seated eye height (from floor)	44.4	48.0	51.5
18	Seated eye height (from seat)	29.4	31.5	33.5
19	Seat height	15.0	16.5	18.0
20	Seat to elbow	8.1	9.6	11.0
21	Thigh clearance	4.5	5.6	6.8
22	Forearm length	17.0	18.7	20.5
23	Elbow to shoulder	13.2	13.7	14.1
24	Knee to floor	20.1	21.7	24.4
25	Chest depth	8.0	9.0	10.4
26	Buttock to inside knee	17.7	18.9	20.1
27	Buttock to outside knee	21.2	23.6	25.0
28	Buttock to heel	40.5	43.8	47.8
29	Foot length	9.6	10.4	11.2
30	Shoulder breadth	16.5	17.9	19.4
31	Waist breadth	8.7	10.7	12.6
32	Hip breadth, sitting	12.7	13.9	15.8
33	Weight	127 lbs.	153 lbs.	192 lbs.

Notes:

1. To allow for relaxed position, deduct 1.2 in. for items 6, 7, 8, 9, 10, and 11;
   2.0 in. for items 16, 17, 18, and 20;
   1.7 in. for the sum of items 20 and 23.

2. An allowance of 1.1 in. for shoe height is included in items 6, 7, 8, 9, 10, and 11; an allowance of 0.4 in. for shoe breadth is included in item 15.

3. Allowance for bulky or restrictive clothing or equipment which must be worn must be determined on an empirical basis. Bulky clothing will have two major effects: 1) it will increase static dimensions such as thigh clearance, chest depth, shoulder width; and 2) it will decrease dynamic dimensions such as arm span and forward arm reach.

Fig. 3-44. Measurements of personnel.

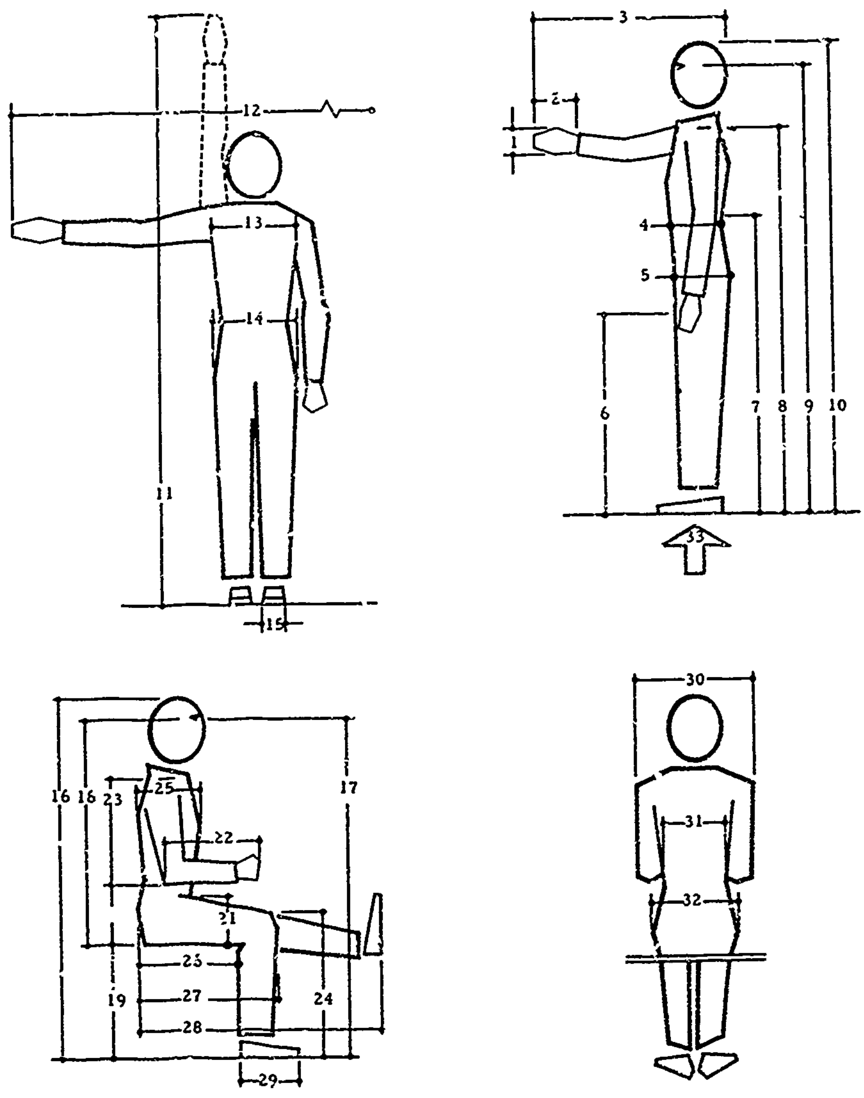


Fig. 3-44 (continued)

c. Use the average as the nominal position or dimension where a range of adjustments is provided (e.g., seat height). The requirement here is to accommodate both the largest and smallest personnel.

* When designing for personnel weight, the designer should:

a. Use the 95th percentile plus a safety factor when designing load bearing structures.

b. Use the 5th percentile when calculating the minimum inertial value to be expected of human work effort.

* When more than one operator must use the panel or console consideration should be given to minimizing visual and movement interference.

The problem facing the designer is whether the design of workspace should be based on the largest, the average, or the smallest body dimensions, or some combination of these. Although average (50th percentile) dimensions for various parts of the body and range of movements are given in Figure 3-44, it should be emphasized that there may be no such thing as an average man in each and every respect. An average is simply a point along some scale, and to use average dimensions for all design considerations will inconvenience, or even eliminate, a large portion of the potential users of the work station or equipment. In the design, the value of the measure to be used should be determined in accordance with the functions to be served. This can best be described by an example: The problem involved is to design a console for seated operators whose function is two-fold: (1) to operate controls on the console and (2) to be able to see over the top of the console to view additional displays on another set of panels at a relatively low position with respect to the floor, such as is the case with the Fire Control Console and the DATICO Panels in the SSB(N)598 and 608 Classes. In order for most operators (i.e., 95%) to be able to see over the top of the console, measures for the 5th percentile must be used. To place the operator at the console, sufficient leg room should be provided for the longest legs. Hence, the design is for the 95th percentile. Finally, seat length, being a fixed dimension, would require the use of the 5th percentile (i.e., to accommodate the smallest man).

3. Design of Panels and Consoles

The design of control and display panels and consoles requires that:

a. Space and support equipment be provided for the operator so that he may use the panel or console comfortably and effectively whatever the time period involved.

b. Controls be selected and/or designed and positioned on the panel or console such that they can be operated accurately and efficiently.

c. Displays be selected and/or designed and positioned on the panel or console such that they can be interpreted accurately and rapidly.[+]

3.1 Position of Operator

This subsection discusses the position of the operator in front of the panel or console, the over-all configurations for panels and consoles, and the placement and operation of controls and displays on panels and consoles.

Factors such as operation and maintenance requirements, available space, and length of work period will determine whether a sit, stand, or sit-stand work station is provided for the operator. The advantages of each of the positions is summarized in Table 3-15.

The optimum and limiting dimensions for visual and manual operations for both seated and standing positions are discussed in the following subsections.

[+] Final decisions about controls and displays cannot be made until decisions are reached about how much space is available, how many panels or consoles should be provided, and where they will be located.

Table 3-15

Comparison of Seated and Standing Positions[+]

Seated	Standing
Minimizes operator fatigue	Increases mobility of operator
Increases operator stability	Permits large control motions
Permits maximum use of pedal controls	Permits utilization of body weight in exerting forces
With adjustable seat height, accommodates wide range in size of operators	Saves space required for seats
Provides body support when operator exerts horizontal fore-aft forces	Permits one operator to cover large work area

[+] Sit-stand arrangements retain the advantages of a standing position while reducing fatigue. (See Fig. 3-44)

3.1.1 Performance of Visual Operations

The dimensions for the visual workspace are determined by the distance and angle at which the operator must view the panel or console and, where controls are involved, the reach distance. The discussion here will be confined to the viewing distance and angles for observation of panels and consoles to be used by single operators.[++]

[++] Reach distance is discussed in the following subsection on Performance of Manual Operations, pages 169 ff.

The following definitions provide background for the guidelines on the visual work area:

a. The standard line of sight is perpendicular to both the lateral and the vertical axes of the head, independent of eye movement. For a seated or standing operator, the vertical axis of the head is tilted slightly forward due to normal slouch (assumed to be about 5 deg); hence the standard line of sight is approximately 5 deg below the horizontal.

b. The normal line of sight, when eyes are at rest, is approximately 10 deg below the standard line of sight, or 15 deg below the horizontal. (See Fig. 3-45.) In either seated or standing positions of the operator, the eyes naturally assume a small downward cast.

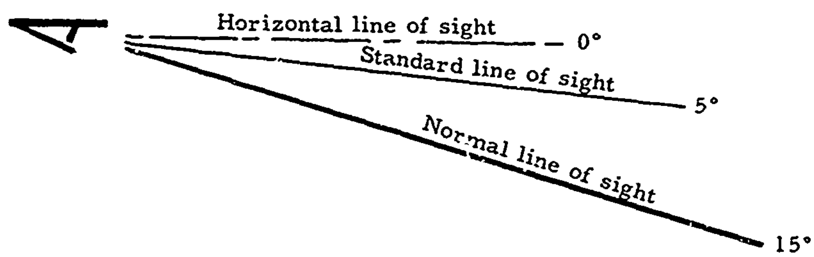


Fig. 3-45. Lines of sight.

c. The maximum viewing distance, as specified by current convention (and as adopted as a standard in this handbook), is 28 in. for normal operation. This dimension represents the distance from the bridge of the nose to the center of the object being viewed, i.e., the length of the line of sight. (For precise visual measurements, this distance is measured from the center of the eye; however, since both eyes are involved simultaneously, the bridge of the nose is a satisfactory approximation for workplace layout considerations.)

d. The viewing angle is the angle defined by the line of sight and the plane of the viewed surface.

e. The optimum angular visual field is represented by the angle, measured horizontally and vertically from the normal line of sight, through which the operator can view displays or controls with speed and accuracy by means of eye rotation alone. (Fig. 3-46.) Shifts from one visual fixation point to another are accomplished more quickly by eye rotation alone when they involve: 1) several such shifts in close succession, and 2) only a small (less than 15 deg) angular change. Changes in the point of fixation that last longer than a few seconds or require a greater angular change in the line of sight usually involve both head and eye motion. The operator generally prefers to hold his head stationary in order to establish a better orientation with respect to his surroundings.

f. The maximum angular visual field is represented by the angle through which the operator can view displays by combined head and eye rotation without straining neck or eye muscles. (Fig. 3-46.) It is measured horizontally and vertically from the normal line of sight.

The optimum and maximum dimensions of the visual area are defined both by the angular visual fields and by the viewing distance.

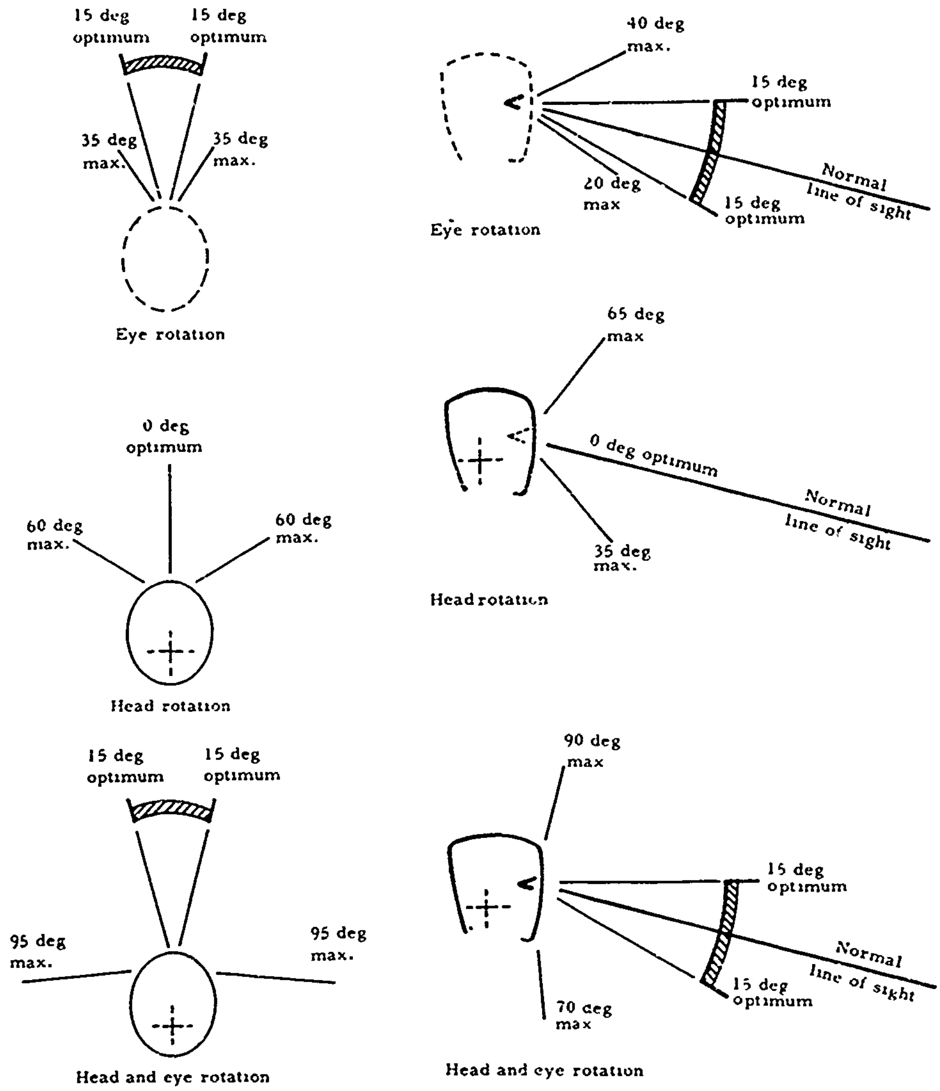


Fig. 3-46. Horizontal and vertical visual fields.

3.1.1.1 Seated Position

* The viewing distance of panels for a seated operator should be no farther than 28 in. and no closer than 16 in.

The maximum limit of 28 in. represents the farthest distance that an operator can reach conveniently from a seated position and hence is based on the assumption that controls, as well as displays, appear on the panel and must be manipulated by the operator. For distances greater than 28 in., properly designed displays (e.g., larger legends, etc.) can compensate for increases in viewing distance. Other considerations, such as space availability for the operator or the equipment, may necessitate some deviation from the recommended standard. However, criteria affecting the location of controls and displays must be considered before accepting any proposed deviation.

* The optimum and maximum angular visual fields for panels to be used by seated operators within the acceptable limits of viewing distance should conform to Figure 3-46.

3.1.1.2 Standing Position

The optimum visual area for a standing operator is not as subject to strict dimensional constraints as is that for a seated operator because a standing operator can face in any direction equally well or can walk from one position to another. If he is not free to do so, the workplace should be so designed that the operator takes either a seated or a sit-stand position. As long as constant attention in one particular direction is not required, displays that involve only occasional reading or viewing can be placed (at the proper height) anywhere around him. Moreover, the capability of the standing operator to change position makes it easier to group related displays, even though some important displays are not in the optimum visual area for all positions of the operator.

* The optimum and maximum vertical angular visual fields for a standing operator should conform to the angles shown in Figure 3-46. The dimensions for the preferred visual area are shown in Figure 3-49.

It is not necessary to specify an optimum or maximum lateral dimension because the standing operator can walk to the front of any display.

3.1.1.3 Orientation of Displays

* The plane in which displays lie should be perpendicular to the normal line of sight wherever possible, and in no case more than 45 deg from the perpendicular.

3.1.2 Performance of Manual Operations

The following definitions provide background for the guidelines on manual workspace:

a. The optimum manual space is that area in which hand-operated controls can be manipulated with the greatest speed and accuracy (Fig. 3-47.) This space is reserved for controls which must be operated frequently or are critical to operations. The placement of controls in the optimum space permits:

   (1) Rapid and accurate identification, reaching, and activation.

   (2) Location of visual displays near the controls.

   (3) Efficient expenditure of muscular energy (particularly for situations where controls must be operated for long periods of time).

   (4) Muscular force to be applied in any direction.

b The over-all manual space is defined by the limiting dimensions of reach. (Fig. 3-48.) Limiting dimensions are expressed in terms of the distance of points in space located along the lateral and vertical axes extending from a basic reference point:

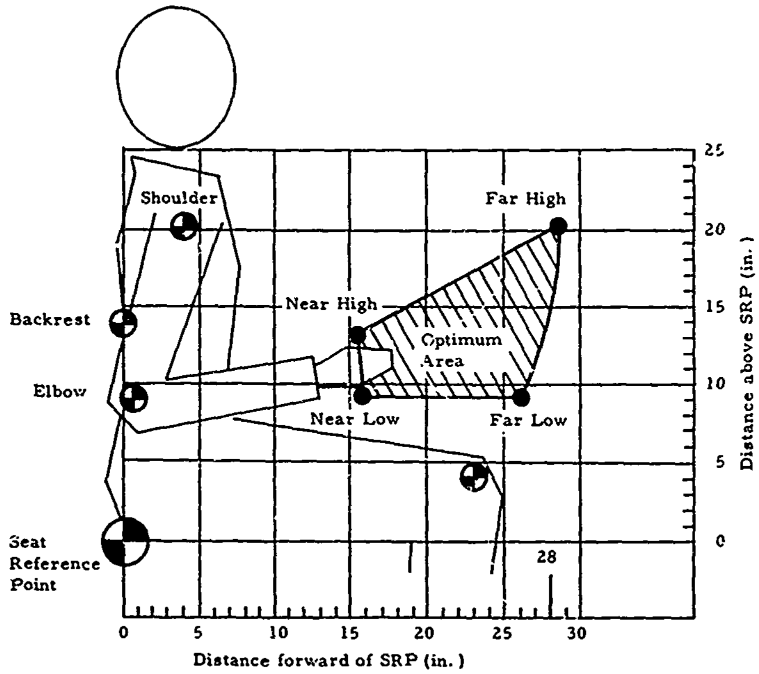


Fig. 3-47. Optimum space for manual operations.[27] (Width of optimum reach space is approximately 24 in.)

(1) For seated operators, as shown in Figure 3-48, this reference is located at the intersection of the middle lines of the seat and the back rest; it is commonly called the seat reference point (SRP).

(2) For standing operators, the reference point is located on the operator's trunk about 10 in. forward of the seat reference point.

3.1.2.1 Seated Position

* The optimum fore-aft workspace for placement of controls for seated positions should conform to the dimensions in Figure 3-47. Determination of the optimum manual area in which controls are to be positioned should be based upon the following measurements of personnel (based on Fig. 3-44):

a. Elbow to center of fist: Use the 95th percentile to assure that controls are not placed too close for use by most operators.

b. Elbow to seat reference point: Use the 50th percentile to assure that an adequate range is available to accommodate most operations.

c. Shoulder pivot point to seat reference point: Use the 5th percentile for vertical distance to assure that controls are not placed too high for use by most operators. (The shoulder pivot point is located approximately 1-1/2 in. below the outer edge of the shoulder--used as the reference point for "shoulder height" measurements--and 4 in. forward, horizontally, of the seat reference point.)

d Shoulder pivot point to center of fist (arm extended): Use the 5th percentile to assure that controls can be conveniently reached by most operators.

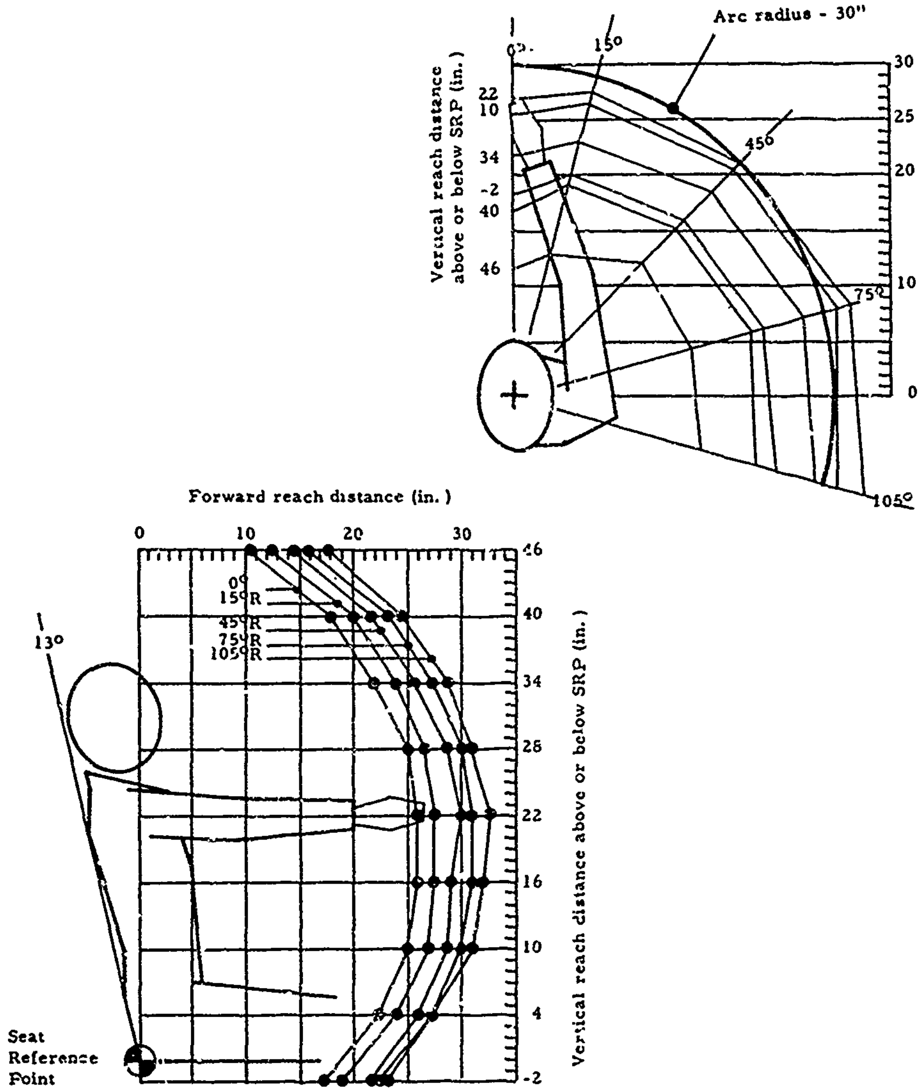


Fig. 3-48. Maximum space for manual operations. (53)

Modifications

Type of Control	Reduce Maximum Reach Dimension By
Toggle switch	2 in.
Rotary selector switch	4 in.
Levers and cranks (require hand grasping)	5 in.

Body Movement	Increase Maximum Reach Dimension By		
	At 0 Deg (Straight Ahead)	At 45 Deg (Oblique)	At 90 Deg (Straight from Side)
Shoulder extended	4 in.	3 in.	Not Applicable
Shoulder extended, trunk rotated	6 in.	4 in.	Not Applicable
Shoulder extended, trunk rotated, trunk bent	16 in.	12 in.	8 in.

Fig. 3-48 (continued)

e. Knee to seat reference point: Use the 95th percentile for both horizontal and vertical distances to assure adequate knee clearance for most operators.

* The limiting dimensions of reach for seated operators should conform to those in Figure 3-48. In practice, these dimensions are subject to modifications depending upon the types of controls to be used, as well as effects of operator shoulder and trunk movement. (See modifications provided in Fig 3-48.)

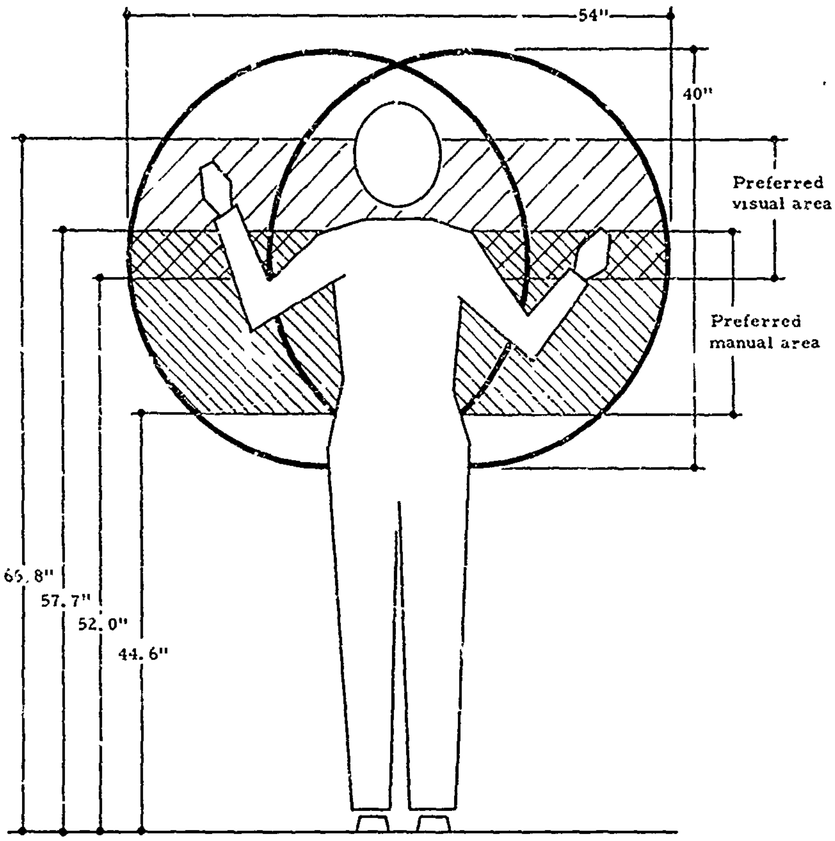
* When all controls cannot be placed within the optimum manual area, locations adjacent to the optimum area should be used.

The desirability of a control location decreases as any increase is necessitated either in the distance above shoulder level or below waist level or in the distance sideward and rearward from the optimum control area.

3.1 2.2 <u>Standing Position</u>

* The preferred upper and lower limits for workplaces in which operations are to be performed by a standing operator should conform to those given in Figure 3-49.[+] The preferred manual area (shown in Fig. 3-49 as 57 7 and 44.6 in. respectively) lies between shoulder and elbow levels for the 50th percentile man when arms are placed at the side of the body.

+ Lateral dimensions are not considered because the standing operator is free to walk from one position to another.



Note: Viewing distance = 20"
Dimensional information is based on the 50th percentile data in Fig. 3-44.

Fig. 3-49. Standing operator workspace.

In order for the preferred area to be within easy operating range of all operators and near-optimum for the majority of potential users, dimensions for the 50th percentile should be used (Fig. 3-44). The area cannot be optimized for both tall and short operators because the area between the lower limit (the elbow height of the tall operator) and the upper limit (the shoulder height of the small operator) would be too small an area to have practical value.

The vertical fore-aft cross-section drawing of the optimum manual area is represented by the location of "near low" and far low" points (in Fig. 3-47) which are approximately 47 in. above floor level.

Lateral dimensions of the optimum manual space should be approximately 30 in. (i.e., groups of controls that are to be operated simultaneously or in close succession should be placed within a lateral distance of 30 in.). If the operator is able to move back and forth between successive control operations, lateral distance is limited only by the time required to move from one control to another.

* The maximum vertical limits for a workplace in which operations are to be performed by a standing operator range from 77 in. above the floor (the maximum height at which a small operator can reach and manipulate controls) to 32 in. above the floor. In practice, these maximum limits should be subjected to the following qualifications:

a. Controls should not be placed on the overhead directly above passageways and/or working positions. The minimum floor-to-ceiling clearance for a tall operator is 75 in., and the maximum height a small operator can reach is 77 in.; hence, the possible overhead work area is only 2 in.

b. Lowest position (maximum displacement) of a control should be at least 32 in. from the floor (knuckle height of a 95th percentile operator is 33.5 in.) in order to prevent excessive stooping, a particularly important consideration in respect to controls that are used frequently or which require heavy force to be applied in their operation.

c. Height which an operator can reach will be limited to the extent he must stretch over an object, such as a table, console, workbench, etc., to operate a control. When the obstruction is below waist level, the operator can bend forward and increase his reach by about 16 in.; however, as the point of reach rises above shoulder level, the gain attainable by bending the trunk decreases progressively to zero at a point directly overhead (Fig. 3-48).

3.2 Configurations of Panels and Consoles

3.2.1 Contours and Slopes of Consoles+

The effectiveness with which the operator performs his tasks will depend, to a large degree, on the over-all configuration of the console. This involves designing the contours and slopes of the console to minimize parallax in viewing displays, locating controls so they can be easily manipulated, and providing adequate space and supports for the operator. There is no configuration for consoles that is acceptable for all applications--each console must be "tailor-made" to fit the operational requirements and space limitations of the particular situation. There are, however, certain configurations which are more effective than others. These are illustrated in Figures 3-50, 3-51, 3-52, and 3-53. Figure 3-50 illustrates surfaces and slopes for seated operations. Figure 3-51 illustrates a console for seated operations where the operator must be able to look over the top of the console. Figure 3-52 illustrates a console for sit-stand operations. Figure 3-53 illustrates a "wrapped around" configuration where the panels are grouped radially about the operator. This arrangement permits more controls and displays to be placed within the operator's manual and visual workspace; however, this configuration is limited to use by a single seated operator.

The various surfaces on consoles can be classified in terms of primary and secondary display and control areas. Each of these

---

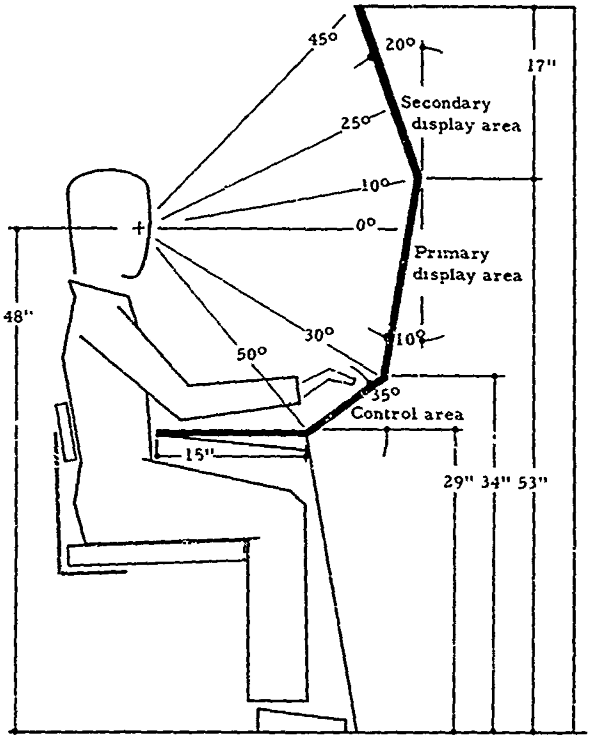
+ Vertical panels with controls and displays such as might be involved on racks of equipment (or "doors" in the case of the Mark 84 Fire Control Subsystem) are not discussed since slopes and contours have little meaning in this situation. It should be noted, however, that the selection and placement of displays and controls on these panels should conform to the guidelines provided for visual and manual workspaces.

areas will be discussed and guidelines for their use will be provided. Console leg and foot space is also discussed

3.2.1.1 Display Surfaces

The primary display surfaces for the console configurations illustrated in Figures 3-50, 3-51, 3-52 and 3-53 are indicated on the drawings. In general, this area corresponds to the optimum angular visual field.

* The primary visual surface on consoles should be reserved for displays which are used frequently and/or



Note: Increase all console height dimensions by 13" for a stand-up console.

Fig. 3-50. Console for seated operation.

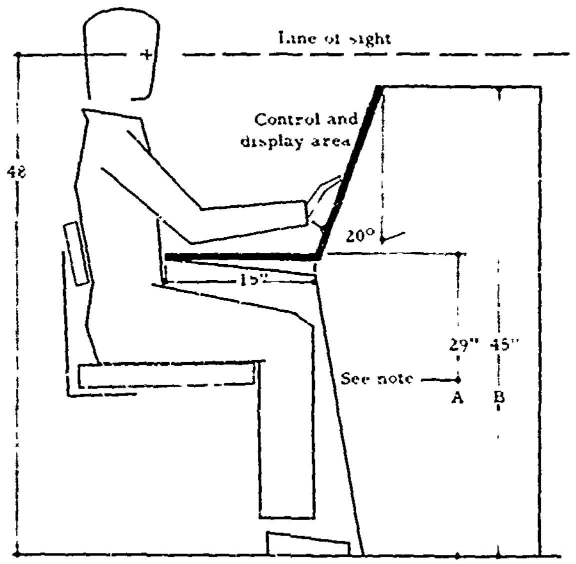
are critical to successful operation. (Special cases where controls and displays are combined or control and display compatibility is important, even though the displays are of secondary importance, may warrant their placement on this surface.)

The secondary display surfaces are also illustrated in Figures 3-50, 3-51, 3-52, and 3-53 and, in general, are located above and/or to the side of the primary display surfaces.

* The secondary visual surface should be used for displays which are used infrequently during operations (e.g., set-up, adjustment), or which are noncritical to operations.

3.2.1.2 Control Surfaces

The surfaces on which to mount controls are indicated in Figures 3-50, 3-51, and 3-52. In general, the control area is below the area



Note: Increase dimension "A" to 42" and "B" to 58' for standing operation with lookover requirement to maintain the same relationships.

Fig. 3-51. Console for seated lookover operation.

where displays are mounted; however, displays which are closely associated with controls can be mounted on these surfaces. The control areas, in general, correspond to the optimum manual space.

3.2.1.3 Work Surfaces

A horizontal (or nearly horizontal) work surface is indicated in Figures 3-50, 3-51, 3-52, and 3-53. Such a surface serves primarily as a work or writing surface or as a support for operator convenience items, such as ash trays, etc. This surface can also be used for locating certain types of controls (e.g., joystick tracking control, etc.).

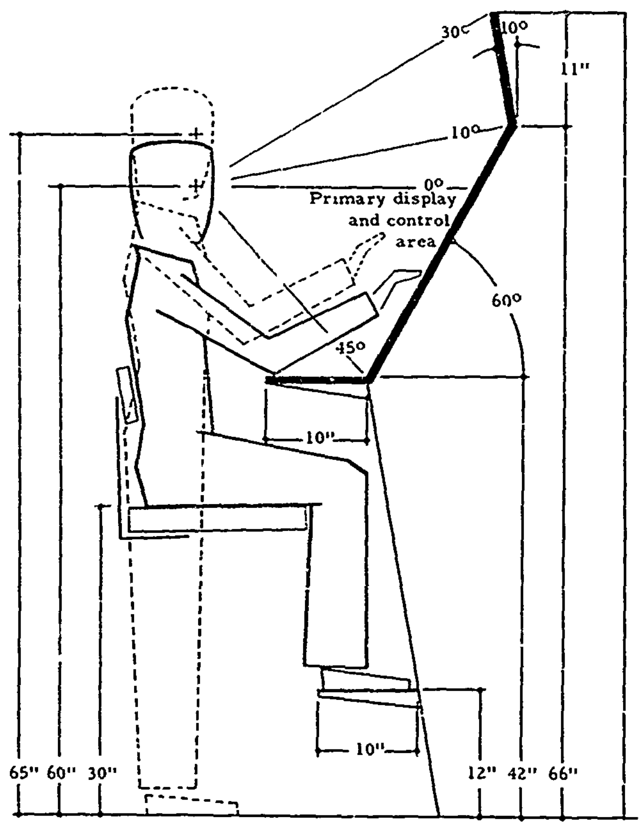


Fig. 3-52. Console for sit-stand operation.

* When a horizontal work surface and control panel are combined (as in Figure 3-50), the work surface should not be more than 15 in. in depth (to permit reaching the panels); the minimum depth should be 10 in. (in order to provide a writing surface).

3.2.1.4 Under Console Area

* The dimensions for leg and foot clearances under consoles should conform to those in Figure 3-54.

3.2.2 Arrangement of Controls and Displays

The placement of controls and displays on panels and consoles should be based on an analysis of operator utilization (frequency, accuracy, sequence, etc.) and the importance of these components to monitoring or controlling system performance. When such an analysis has been made, a sound basis is provided for the guidelines on arrangement of controls and displays which are contained in this subsection. These guidelines are categorized in terms of:

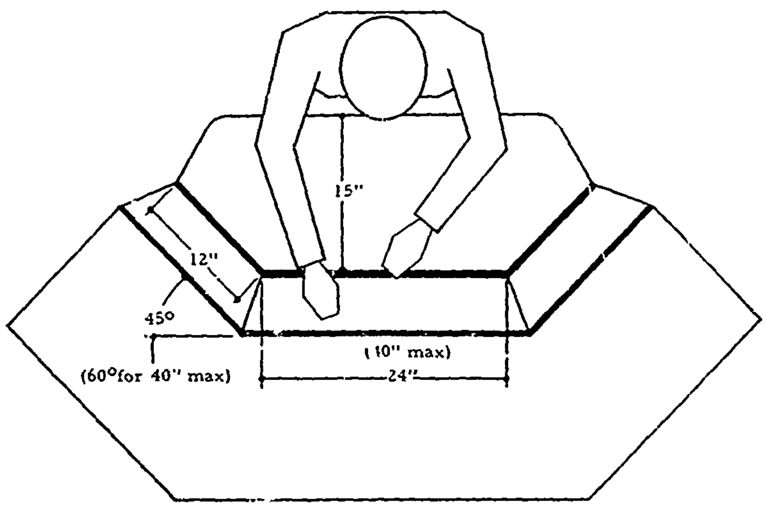


Fig. 3-53. Contour of panels for wrap-around console.

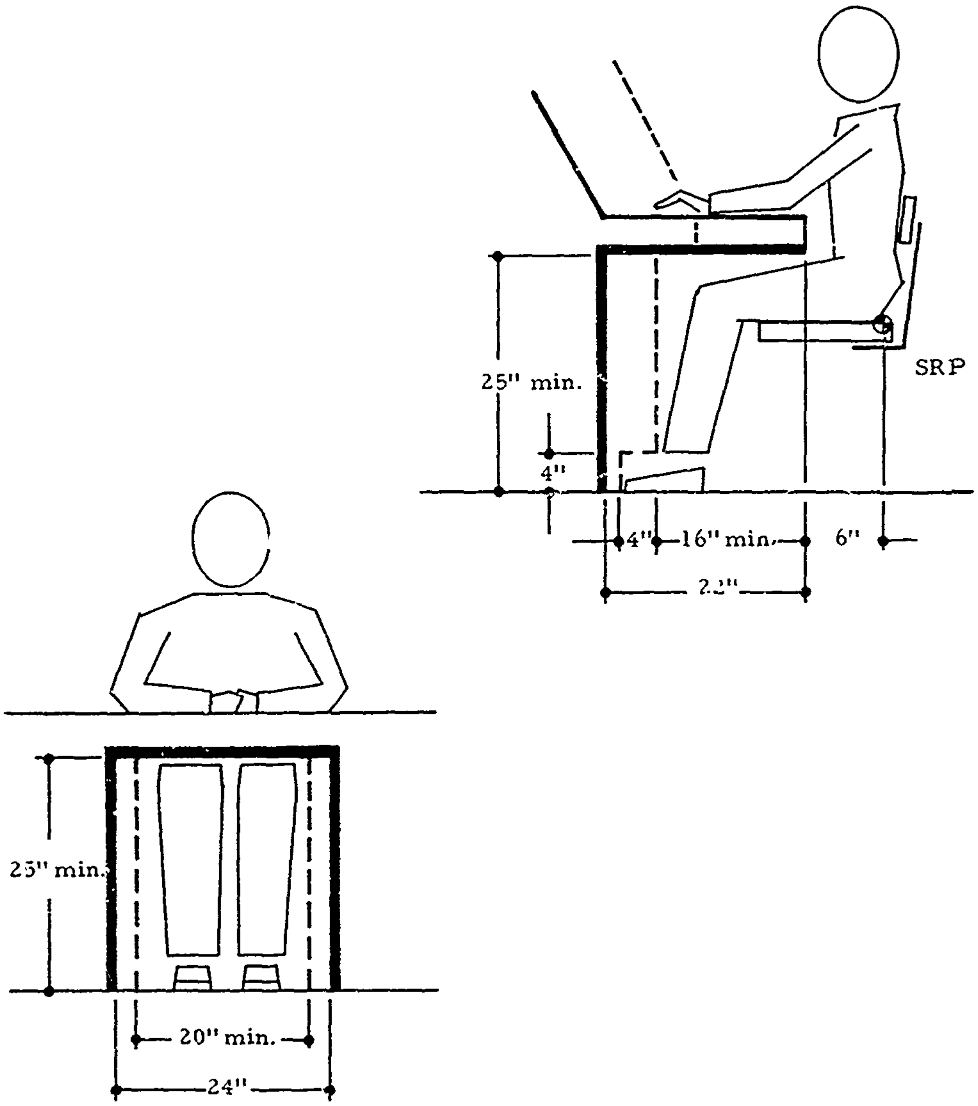


Fig. 3-54. Leg and foot clearances.

a. Priorities for location of controls and displays.
b. Grouping of controls and displays.
c. Association between controls and displays.
d. Spacing between controls.

3.2.2.1 Priorities for Location of Controls and Displays

Priority of location refers to the placement of the most important controls and displays in the optimum visual and manual workspaces on the panel or consoles. To establish the importance of controls and displays the following criteria should be determined:

a. Frequency and duration of use of the control or display.

b. Accuracy and/or speed with which the display must be read or the control activated.

c. Decrease in system performance and/or personnel or equipment safety resulting from an error or delay in using the control or display.

d. Ease of control manipulation in various locations in terms of force, precision, and speed requirements.

* The primary (i.e., highest priority) displays and controls should be placed in the optimum visual and manual workspaces.

* The secondary controls and displays should be placed within the limiting areas for visual and manual workspaces so that they are readily accessible when required (e.g., emergency controls and displays which may not warrant the highest priority in location but still must be accessible if required).

* The controls and displays of least importance during operation should be placed in the lowest priority positions (e.g., setup and calibration controls and displays which are not used during operation).

* When controls and displays may be used by two operators at the same time (e.g., in controlling a vehicle) the following criteria should be applied:

  a. If primary controls and displays are involved, duplicate sets should be provided wherever there is adequate space. Otherwise, controls and displays should be centered between the operators.

  b. If secondary controls and displays are involved, they should be centered between the operators if equally important to each. If the controls or displays are more important to one operator than to the other, they should be placed nearer the operator having the principal requirement for their use.

  c. If direction-of-movement relationships are important, controls and displays should be located so that both operators face in the same direction.

3.2.2.2 Grouping of Controls and Displays

The grouping of controls and displays should be accomplished primarily on the basis of function and sequence of use. Other methods, such as frequency of use, importance, and optimum location (in terms of speed, accuracy, force, etc.) can be applied but are used primarily to establish priorities for location. There is no single technique for grouping that is optimal for all situations and most control and display panels and consoles will reflect combinations of several techniques.

* Functional grouping should be used for controls and displays which are:

  a. Identical in function.
  b. Used together in a specific task.
  c. Related to one equipment or system component.

* Sequential grouping should be used for:

  a. Controls which are operated in sequence.
  b. Displays which are observed in sequence.

* When displays are arranged sequentially (Fig. 3-55) they should meet the following criteria:

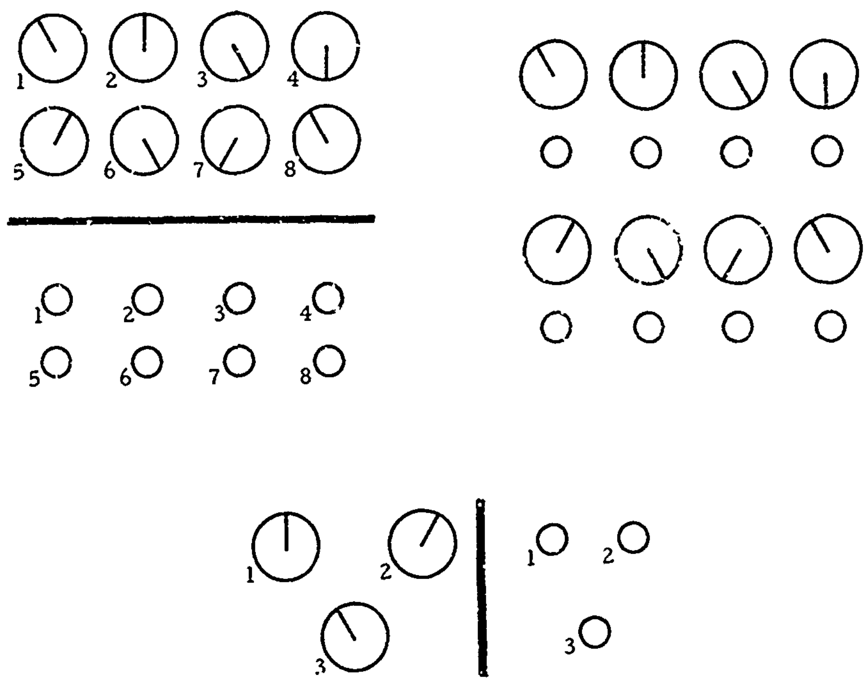


Fig. 3-55. Arrangement of displays and controls for sequential use.

a. They should be aligned so that they are viewed in the following sequence:

   1) Horizontally, from left to right.

   2) Vertically, from top to bottom.

   3) In rows when large numbers of displays are involved; from left to right within a row and from top row to bottom row.

b. They should be grouped together as close as possible (providing it does not make each individual display difficult to interpret).

c. If controls are also involved, they should be aligned in a direction determined by the most effective control-display relationships.

* When controls are arranged sequentially (Fig. 3-55) they should meet the following criteria:

a. When used by the same hand, controls should be arranged so that the operator moves his arm horizontally from one to the next one (providing that control and display locations or direction-of-movement relationships are not violated). +

b. When they cannot be aligned horizontally (as described heretofore), they should be arranged in some other systematic manner (e.g., from top to bottom).

+ See the subsections Association Between Controls and Displays, page 187 ff, and Direction-of-Movement Relationships Between Controls and Displays. page 189 ff.

c. When concentric (ganged) controls are used, the front one (smallest) should be used first, the back (largest) last or in the reverse order, but not randomly.

3.2.2.3 Association Between Controls and Displays

When many controls and displays are to be used by a single operator, their arrangement should aid in the identification of which control is used with which display.

* When a control is to be associated with a specific display, the control should be located so that the operator's hand does not obscure the display.

  a. Controls to be operated by the right hand should be located below or to the right of their associated displays.

  b. Controls to be operated by the left hand should be located below or to the left of their associated displays

* When many displays and controls are on the same panel, they should be arranged in either of the following two ways:

  a. Each display directly above its associated control. All control-display combinations must be located close together so that wrong associations are not made (e.g., controls are associated with the displays above them not below them).

  b. All displays on the upper portion of the panel and all controls on the lower portion. Each control occupies the same relative position as its associated display.

* When rows of displays must be associated with columns of controls (an arrangement to be avoided whenever possible), left should correspond with top;

c. When concentric (ganged) controls are used, the front one (smallest) should be used first, the back (largest) last or in the reverse order, but not randomly.

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  b. All displays on the upper portion of the panel and all controls on the lower portion. Each control occupies the same relative position as its associated display.

* When rows of displays must be associated with columns of controls (an arrangement to be avoided whenever possible), left should correspond with top;

a. Requirements for the simultaneous use of controls.
b. Requirements for the sequential use of controls.
c. Body part being used.
d. Size of the control and the amount of movement required (displacement or rotation).
e. Need for blind reaching (i.e., the need to reach for and grasp the control without seeing it).
f. Effects on system performance of the inadvertent use of the wrong control.

Specification of exact distances by which to separate controls is primarily dependent on analysis of the task to be performed (and the space available), hence, only minimum and desirable dimensions are presented in Figure 56 for the separation of controls under various conditions of use.

a. The minimum separation is the smallest acceptable distance between adjacent controls when the operator is located in a stationary workplace having good environmental conditions and when controls are placed within the optimum manual area.

b. The desirable separation is the preferred distance between adjacent controls which are operated intermittently.

3 2 3 Direction-of-Movement Relationships Between Controls and Displays

The direction of movement of controls should be related appropriately to the change they induce in their associated displays, equipment components, and/or the system as a whole. Appropriate direction-of-movement relationships will improve operator performance in:

a. Speed of reaction or decision time.
b. Correctness of initial control movements (i.e., reducing movement in the wrong direction, called "reversal error").
c. Speed of control adjustment.
d. Precision of control adjustment.
e. Speed of learning

Control	Type of Use	Recommended Separation (inches)	
		Minimum	Desirable
Push button	One finger - randomly+	1/2	2
	One finger - sequentially	1/4	1
	Different fingers - randomly or sequentially	1/4	1/2
Toggle switch	One finger - randomly	3/4	2
	One finger - sequentially	1/2	1
	Different fingers - randomly or sequentially	5/8	3/4
Cranks and Levers	One hand - randomly	2	4
	Two hands - simultaneously	3	5
Knobs	One hand - randomly	1	2
	Two hands - simultaneously	3	5
Pedals++	One foot - randomly	A = 8 B = 4	10 6
	One foot - sequentially	A = 6 B = 2	8 4

+When finger or hand-operated controls are used randomly and are "blind positioned," they should be separated by at least 5 in. when mounted in the optimum manual area. This separation should be progressively increased to 12 in. as the location of the control approaches the periphery of the limiting manual dimensions.

++Either dimension A or dimension B should be met, preferably A.

Fig. 3-56. Separation between controls.

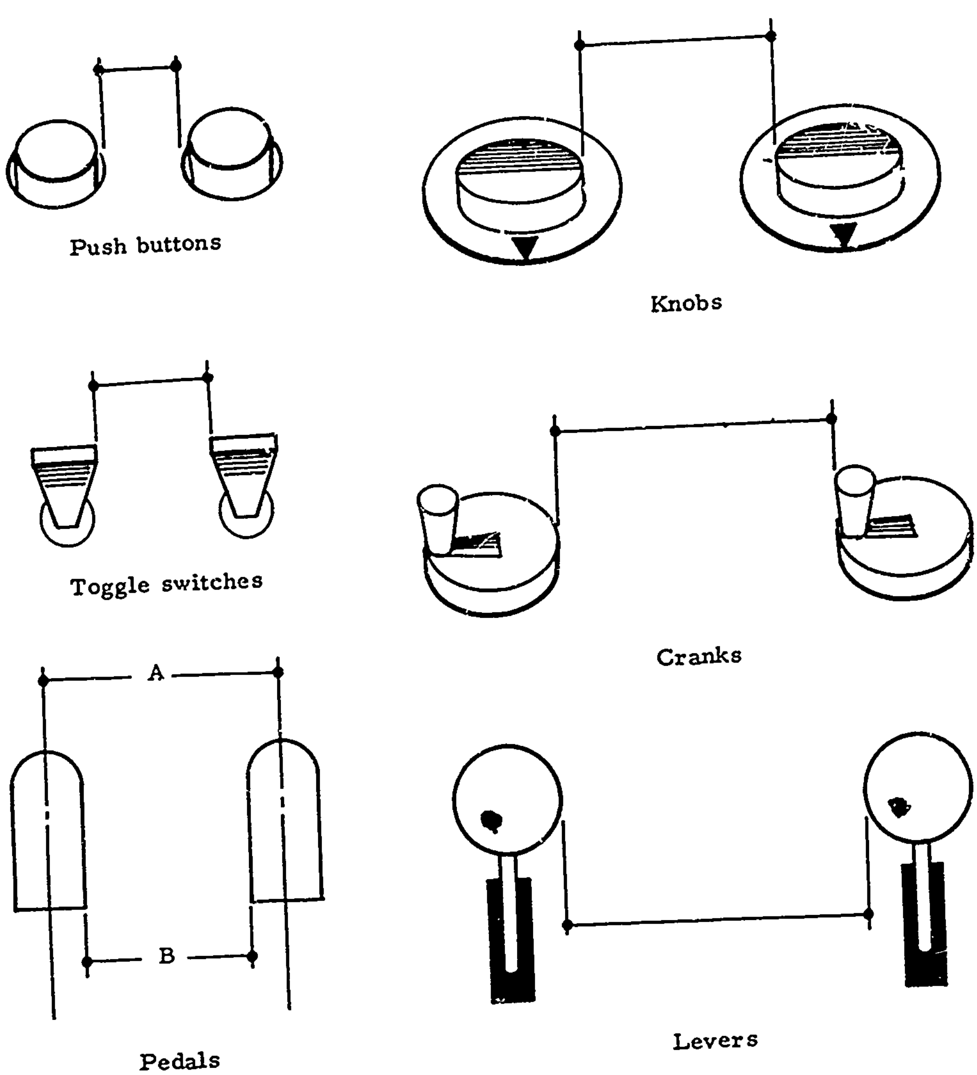

Fig. 3-56 (Continued)

The importance of direction-of movement relationships increases directly with task complexity, discontinuity or number of interruptions in the control sequence, and/or degree of stress or anxiety associated with the tasks. These relationships are relatively unimportant if the operator has a simple repetitive task.

The direction-of-movement relationships recommended here are made to satisfy one or more of three basic requirements:

a. Natural relationships.+
b. Existing design practice.
c. Standardization and consistency.

* Control movements should be consistent between equipments.

* Controls and displays should be placed in front of the operator whenever possible so that direction of movement relationships will not be ambiguous.

* Direction of movement of controls and displays should be related to the purpose underlying each control movement rather than to any particular mechanism or method of actuation used to perform the desired function.

For example, if the operator wishes to lower temperature, opening a vent which will admit cool air or closing a vent which has been admitting hot air need not by itself be related to the control movement. The control movement should be related to the basic purpose: to raise temperature (upward movement, clockwise movement, etc.) or to lower temperature (downward movement, counterclockwise movement, etc.).

* Direct movement relationships should be used whenever possible, particularly when they result in vehicle

+ Natural relationships refer to control movement habit patterns which are consistent from person to person without special training or instructions (i.e., they are responses which individuals make most often and are called "population stereotypes"). For example, an upward movement of a toggle switch is almost always related to "On" as opposed to "Off."

movement (i.e., a movement of the control to the right should result in a movement to the right of an instrument pointer, a right turn of the vehicle, etc.).

* Controls which are related to the direction of movement of the vehicle in which they are mounted should not be located so that the operator must face rearward to use them. In such situations, motion relationships are ambiguous with respect to left-right, clockwise-counterclockwise, and forward-rearward.

3.2.3.1 Rotary Controls and Operator Orientation

In using rotary controls, the operator orients himself with a certain point on the control; he perceives the control as moving in the direction in which this point is moving:

a. With rotary control movements in a horizontal plane, the operator orients himself with respect to the forward point of the control.

b. With rotary control movements in a vertical plane, the operator orients himself with respect to the top of the control.

c. With a rotary control which is largely concealed, the operator responds to the exposed portion of the control as if it were a linear control.

* When the control affects the direction of movement of a vehicle, the point of the control with which the operator is oriented should move in the same direction as the desired direction of the vehicle.

* The axis of rotation for the control should parallel the corresponding axis of rotation of the vehicle (provided the resulting control movements do not cause undue operator discomfort).

3.2.3.2 Linear Controls and Operator Orientation

The direction of linear control movements for on-off (or increase-decrease) controls such as levers and toggle switches is determined by the orientation of the panel on which these controls are mounted with respect to the operator.

* For controls mounted on vertical panels, "On" or "Increase" should be an upward movement, "Off" or "Decrease" a downward movement (Fig. 3-57).

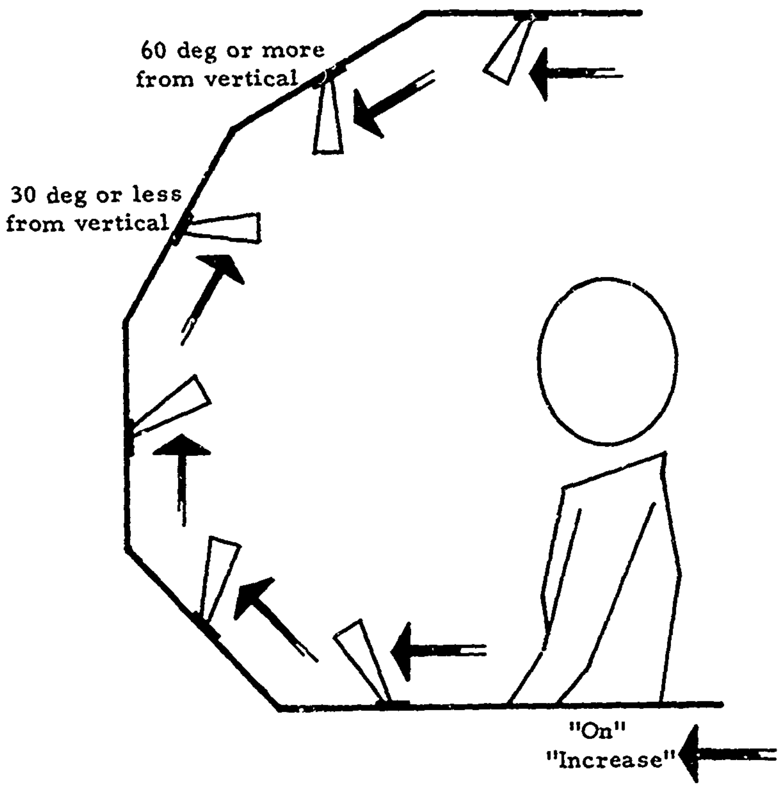

Fig. 3-57. Direction-of-movement of linear controls.[27]

* For controls mounted on horizontal overhead panels, "On" or "Increase" should be a forward movement, "Off" or "Decrease" a rearward movement.

* For controls mounted on upward facing horizontal panels, "On" or "Increase" should be a forward movement, "Off" or "Decrease" a rearward movement.

* For controls mounted on sloping panels, there may be no sharply defined division between up-down and forward-rearward control movements. (Fig. 3-57.) When panels are below eye-level, this is unimportant because forward and upward movements both require the operator to apply force in the same general direction. However, for panels above eye-level a forward movement is opposite that of an upward movement; therefore, to avoid ambiguous situations:

  a. For overhead panels tilted approximately 30 deg or less from the vertical, controls should be actuated as if the panel were vertical ("On" or "Increase" should be an upward movement).

  b. For overhead panels tilted approximately 60 deg or more from the vertical, controls should be actuated as if the panel were horizontal ("On" or "Increase" should be a forward movement).

Operators cannot make accurate estimates of tilt angles; therefore, overhead panels should not be placed at a 45 deg tilt. Overhead panels should be either less than 30 deg or greater than 60 deg from the vertical.

* When surfaces at slight angles to each other are joined to form a continuous control panel (e.g., a console on which control panels are arranged radially about the operator) control movements should be consistent throughout the panel. All movement relationships should be the same as those established for the central panel. In most instances, it is desirable to include an artificial break in the panel surface, viz., a conspicuous line.

3.2.3.3 Rotary Controls Used With Rotary Displays

* When the display has a moving pointer and a fixed scale, a clockwise rotation of the rotary control should result in a clockwise rotation of the pointer. (Fig. 3-58.)

* When the display has a moving scale and a fixed pointer, it will usually cause direction-of-movement inconsistencies. For recommended practice, see page 32.

* A rotary control should be on the concave side of a rotary display when the display movement traverses less than a full circle.

3.2.3.4 Rotary Controls Used With Linear Displays

* When a rotary control and a linear display are in the same plane, the part of the control adjacent to the display should move in the same direction as the moving part of the display.

* A rotary control should not be placed above any display or to the left of a vertical display. (This avoids conflict between the principle above and the principle that a clockwise control movement should result in either an upward or rightward pointer movement.)

3.2.3.5 Linear Controls Used With Rotary Displays

* When there is no direct linkage between control and display, a linear control may be used with a rotary display.

* When there is a direct linkage between control and display:

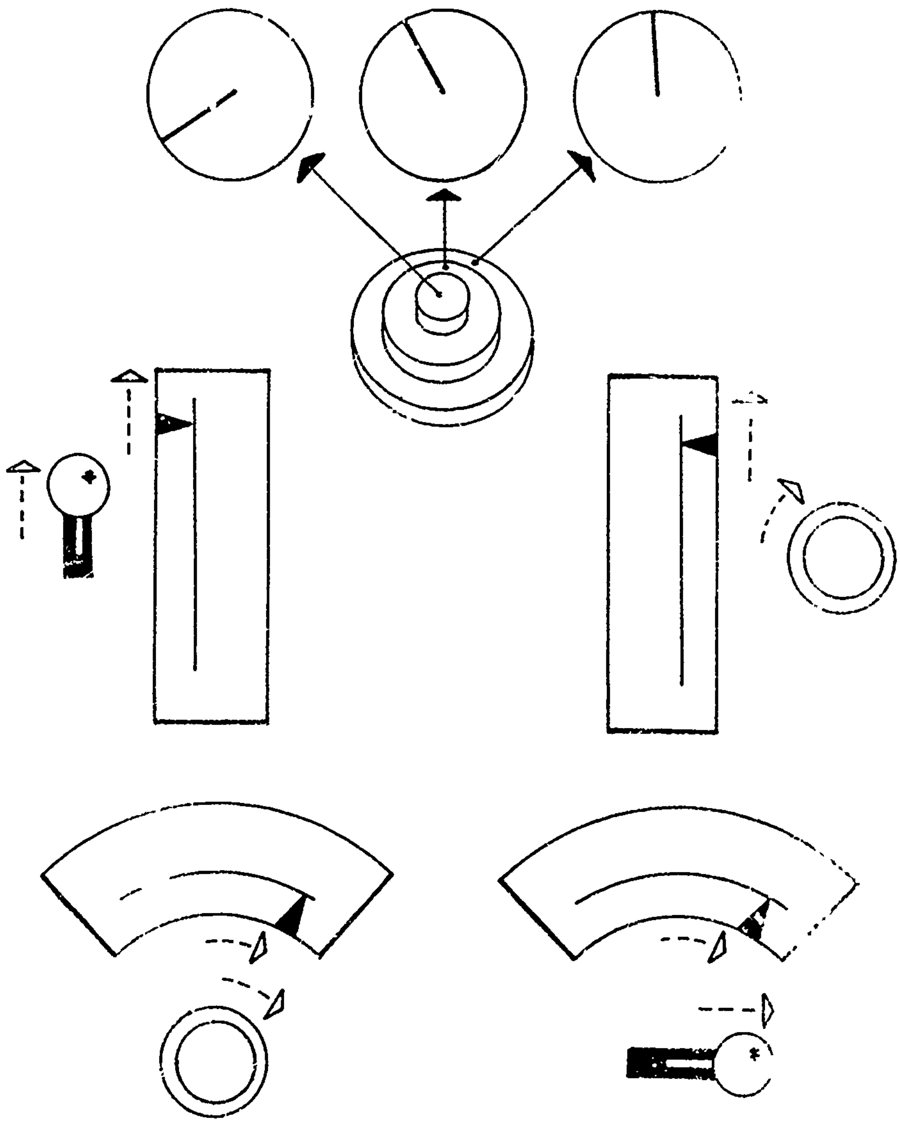

Fig. 3-58. Direction-of-movement relat · h between controls and displa ·

a. A rotary control should be used if the indicator moves through an arc of more than 180 deg.

b. A linear control may be used provided:

(1) The indicator moves through an arc of less than 180 deg.

(2) The path of control movement parallels the average path of the indicator movement.

(3) The indicator and control move in the same relative direction.

3.2.3.6 Valves

For rotary type controls, the "expected" direction of control movement to cause an increase would be to the "right" or "clockwise." However, contrary to this expectation, valves conventionally turn clockwise for "Off" or "Close" and counterclockwise for "Open." Furthermore, the "Off" or "Close" valve action may either increase or decrease the function or process affected, e.g., pressure.

* When valve controls are used, their movement should be in the direction "expected" of rotary controls (i.e., clockwise to "Increase" or "Open" and counterclockwise to "Decrease" or "Close"). This expected direction of control movement should be used both in the presence or absence of an associated display movement (Fig. 3-59). In addition, valves should contain labels that indicate the end purpose served, e.g., "Raise" or "Drain," along with an indicator (arrow) to show the direction the valve should be turned to attain the desired end

* To avoid ambiguities caused by population stereotypes, it may be advisable to replace the conventional valve handle design, where feasible, with a lever, crank, or crossbar.

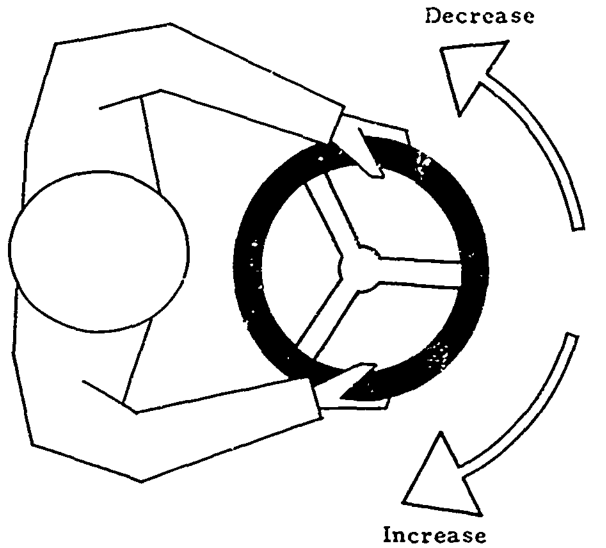

Fig. 3-59. Direction-of-movement relationships for valves.

3.2.3.7 Push-Pull (Plunger-Type) Controls

Such controls, which project from the panel surface on which they are mounted, are not recommended for continuous type activity The pushed-in position on these controls is generally associated with "Off" or "Decrease." This control movement, particularly when the control is mounted on the front plane, conflicts with the usual forward-to-increase control movements.

3.2.3.8 Spring-Loaded Unidirectional Controls

Direction-of-movement relationships do not apply to simple on-off or reset controls (as a trigger or push button) which are spring loaded, move in only one direction and are activated by applying force in that direction.

3.2.3.9 Direction-of-Movement Relationships in Tracking[+]

Direct control-display and control-equipment movement relationships are possible in tracking tasks where the position of the controlled object (i.e., cursor, marker, "hook," or target follower) is directly dependent upon the position of the control. This is called position control. However, for other types of tracking (such as rate control, acceleration control, etc.) direct movement relationships do not apply to the usual position orientation. For example, in rate control, the position of the control directly affects the velocity of the controlled object (and, indirectly, its position). Any movement of the control to the right of the null position imparts a rightward velocity to the controlled object; the farther the control is to the right (or left) of its null position, the greater the rightward (or leftward) velocity. Thus, a change in the direction of movement of the control may or may not result in a change in the direction of movement of the controlled object. In the case where a control is moved to the left, stopped, and then returned rightward toward its null position, the control reversal causes the controlled object to reduce its velocity while maintaining its original direction (left). A change in the direction of movement of the controlled object will not take place until the control is moved rightward beyond the null position.

* Appropriate direction-of-movement relationships can be made to apply to all tracking situations in the following manner:

a. With all tracking control systems (e.g., position, velocity or rate and acceleration), starting with the controlled object at rest, its initial movement should be in the same direction as that of the control. For example with pure acceleration control, movement of the control knob or stick to the right should cause the controlled object to accelerate (speed up at an increasing rate) to the right when starting from rest.

[+] See Fig. 3-38, Position, Rate, and Rate-Aided Control, Page 106.

b. With mixed or aided-tracking control systems (e.g., position-plus-rate), starting with the controlled object at rest, its initial position, velocity, acceleration, etc., movement should be in the same direction as that of the control. For example, in rate-aided (position-plus-rate) control, movement of the control knob or stick a fixed distance to the right should cause the controlled object to move immediately to the right (position component) and then continue moving to the right with a given velocity (rate component).

In the special case of a rigid control where there is no perceptible movement of the control, the direction in which force is applied should be considered equivalent to "direction-of-movement."

3.3 Surface Finish and Markings for Panels and Consoles[+]

3.3.1 Finish Color and Gloss

Since the surface of a panel provides the background against which controls and displays appear, the color of the surface and its diffusion and specular reflection properties can enhance or degrade effectiveness with which such components can be used. However, the exact color which panel surfaces are painted is relatively unimportant provided sufficient contrast is maintained between the critical features of the components and the panels and reflection is properly controlled.

* The gloss of finished panels should be 5 units or less (as measured by the American Society for Testing Materials Standard Method D532).

* The proportion of incident light reflected from panel surfaces should be between 20% and 30%, and it should be distributed evenly over the panel surface.

[+] The guidelines contained in this subsection apply to controls and displays as well as to the panels themselves.

* The color to be used for the surface finish of panels must insure that sufficient contrast is provided between letters or markings and the background under expected conditions of illumination.

  a. If an area is illuminated by normal white lighting at all times, panel color may be varied to indicate functional areas or functional groupings of controls and displays.

  b. If an area is subjected to illumination by both white and low-level red luminaires, the panel surface should be finished in a very dark grey or (preferably) black. (Under conditions of red illumination, markings on panels are usually backlighted and, when not transilluminated, appear white under normal white light.)

3.3.2 Markings

Any form of information, alphanumeric or symbolic in nature, that is painted, printed, engraved, or otherwise attached to a panel or control or display component is classified as a marking. Markings whose primary purpose is to identify some detail, such as the manufacturer, type, function, or content, are termed labels. Legends refer to markings whose purpose is to present information other than simple identification, such as operational instructions, code description, and information on annunicator or legend indicator lights.

The location, content, and composition of markings are important to operator efficiency because such considerations influence the ease and accuracy with which controls and displays can be used. The visual acuity of the viewer (i.e., his ability to distinguish fine detail) under various illumination levels and operating conditions will be affected by the contrast between the object being viewed and its background, which, in turn, is affected by the configuration and content of individual markings. Equally important, of course, is the requirement that markings be imprinted and affixed in such a manner that they remain impervious to abrasion or disfiguration and that they can be easily cleaned.

3.3.2.1 Location

* Markings containing operational procedures, block diagrams, warning information, etc., should be placed near the equipment items involved in the procedure or function described.

* Markings containing information irrelevant to equipment operation, such as manufacturers part numbers, trade names, maintenance instructions, etc., should be placed outside of the operator's central field of view when he is positioned at the equipment or console (e.g., markings that are pertinent only to equipment maintenance should be oriented in such a manner that they can be viewed only from the maintenance position).

* Markings should be so positioned that they are not obscured by and do not obscure other equipment parts or components.

* Labels which identify units (e.g., ANGLE SIMULATOR) should be placed in the center and at the top of the units to which they refer.

* Labels which identify controls and displays should be placed above and close to the units to which they refer.

* Legends should appear on the display or control components to which they refer.

3.3.2.2 Content

* Markings should consist of a common word or words that are readily understood and ordinarily used by the expected users of the equipment.

* Markings should be brief, but not so cryptic as to be ambiguous or confusing.

* Abbreviations and symbols should be avoided if possible. If it is necessary to use abbreviations, they

should conform to the nomenclature list which was developed for the FBM system [68] or to MIL. STD. 12B[1]. If it is necessary to use symbols, they should be common and meaningful and accompanied by a plate located on the console which contains pertinent definitions.

* Controls and displays should be labeled according to function. Units having the same function but appearing in several different locations should have similar identification labels or legends.

* Panels and consoles should be labeled according to acceptable nominal designation or military identification.

* Legends appearing on indicator lights should be used only to transmit information about the following:

  a. Status of the equipment (e.g., "On," "Ready," etc.).
  b. Function of the equipment (e.g., "Align").
  c. Action required (e.g., "Fire," "Hold," etc.).

3.3.2.3 Composition

The style, size, and spacing of individual characters and of groups of characters must be such that both detail and import are evident under various operating conditions and levels of illumination. General criteria relevant to markings and their composition include the following:

* Labels (and brief legends) should be printed in capital letters.

* Operational instructions, code descriptions, checkout or testing procedures, etc., should be composed with extended spacing and printed in capital and lower case letters.

* Legends on indicator lights or lighted push buttons should consist of black opaque characters on a light translucent background and should be legible in the "Off" position.

* When transilluminated labels are used (for controls and displays on equipment employed under low levels of ambient illumination), markings should appear white against a dark background.

  When front-lighted labels are used on panels, markings should appear as dark (black) characters on a light background.

* The visibility of critical details of characters is dependent on their strokewidth and gapwidth, which are usually of the same order of magnitude. Table 3-16 provides character dimensions for minor-, intermediate-, and major-size characters which should be used in conjunction with a 28-in viewing distance for both opaque and transilluminated characters

A person with acceptable vision (Snellen rating of 20/40) for the Armed Forces can resolve detail down to 2 min. of visual angle under good conditions of illumination and contrast. Since 2 min. is a threshold level, and since it is unrealistic to assume that all displays and controls will be viewed under optimum illumination and contrast, the minimum strokewidth size should be somewhat higher than 2 min. in order to insure good legibility. The recommended character dimensions in Table 3-16 conform to such a requirement. The size recommended for the strokewidth of the smallest character will subtend an angle of approximately 2.5 min. Where feasible, that dimension should be used as a minimum under acceptable illumination. However, if space requirements necessitate a variance, the dimension for character height can be reduced to 0.094 in., which approximates a subtended angle of 2 min. at the 28-in. viewing distance. This reduction in size must be countered by manipulation of two other variables affecting legibility, namely, contrast and illumination. Conversely, if it is necessary to overcome the effects of insufficient illumination or if a requirements exists for attention value, the minimum size specified can be increased, space permitting (Table 3-2 gives recommended illumination for specific categories of tasks.)

Table 3-16

Panel Marking Dimensions and Styles

Dimensions

	Size Category		
	Minor	Intermediate	Major
Character height	0.125 in.	0.156 in.	0.219 in.
Point size (approximate)	14-point	18-point	24-point

Type Styles

	Representative Type Style	Desired H/SW Ratio
Opaque Lettering, High Contrast, Light Panel	a. Alternate Gothic b. Futura Medium c. Copperplate	Minimum 6:1 Maximum 8:1
Back-lighted Lettering, Dark or Black Panel	a. Futura Light	Minimum 10:1 Maximum 12:1

* Suggested size categories for markings for black on light, white on dark, and back-lighted characters include the following:

a. Major characters (i.e., 0.219 in.) should be used for panel labels.

b. Intermediate characters (i.e., 0.156 in.) should be used for display or control identification markings.

c. Minor characters (i.e., 0.125 in.) should be used for control position markings and legends on indicator lights.

d. If there is a requirement for a fourth category (e.g., a label for a group of related controls and displays), this can be obtained by adding a size category of 0.094 in. Then the size categories would be:

1) Panel labels--0.219 in.
2) Control/display groups--0.156 in.
3) Component label--0.125 in.
4) Component minor markings--0.094 in.

Other criteria pertinent to character dimensions include the following:

* Preferred height-to-strokewidth (H/SW) ratios include the following:

a. For high contrast black on white or white on dark characters (assuming 1 to 20 ft. L brightness), the preferred H/SW ratio is within the range 6:1 to 8:1 (Table 3-16).

b. For panels used under dark adapted conditions, back-lighted or luminous characters of thinner strokewidth should be specified. The preferred H/SW ratio for translucent markings is within the range 10:1 to 12:1 (Table 3-16).

For back-lighted or luminous markings, the single variable which most affects the strokewidth consideration is brightness. Excessive brightness will reduce character legibility (e.g., distort distinctive feature of some characters) under dark adapted conditions due to the phenomenon of

irradiation.[+] Highly luminous lettering on a dark background should have a H/SW ratio within the range 12:1 to 20:1 to compensate for irradiation.

* Average width of characters (letters and numerals) should be between 65% and 80% of their height. Wider characters (up to a 1:1 width-to-height ratio) are permissible, but for a given height they require more space and, therefore, are not practical for most label or legend applications.

Obviously, the letters M, W, and I and the numerals 1 and 4 require considerable variance from the average width. The geometric proportions for these characters are determined by the type font. The use of wider characters (up to a 1:1 width-to-height ratio) can be justified in cases where the characters are applied to a curved surface (e.g., on a mechanical counter) or where characters must be viewed from an unfavorable angle.

Table 3-16 also specifies the recommended type font and the type point equivalent for each character size. Futura Medium, Alternate Gothic, Copperplate, or similar plain block style should be used for black-on-light and white-on-dark lettering (Fig. 3-60). Futura Light or similar light strokewidth style should be used for back-lighted lettering. These type fonts are given as examples of panel markings, since they approach the dimensions of characters recommended in this section.

The following guidelines should be applied to the spacing of markings:

* Letters and numerals should be so spaced that the area between adjacent characters is approximately

[+] Irradiation is a phenomenon in which black lines on white appear narrower than they actually are and white lines on black appear wider than they are. This phenomenon occurs primarily when the eyes are adapted to darkness.

equal (optical spacing). A "rule of thumb" is to make the space between characters equal to one-half the average width of the characters.

* The spacing between groups of letters and numerals should be equal to the average character width of the type face used.

* Spacing between lines of characters should be equal to the height of the capital characters. (This requirement can be modified to some extent if space constraints in a particular situation so require.)

Alternate Gothic		Futura Medium
ABCDEFGHIJKLMNOPQRSTUVWXYZ 1234567890	10 point (0.094" approx.)	ABCDEFGHIJKLMNOPQRSTUVWXYZ 1234567890
ABCDEFGHIJKLMNOPQRSTUVWX 1234567890	14 point (0.125" approx.)	ABCDEFGHIJKLMNOPQRSTU 1234567890
ABCDEFGHIJKLMNOPQRSTUV 1234567890	18 point (0.156" approx.)	ABCDEFGHIJKLMNOPQ 1234567890
ABCDEFGHIJKLMNOPQRST 1234567890	24 point (0.219" approx.)	ABCDEFGHIJKLMNOP 1234567890

Fig. 3-60. Representative type styles

4. Design of Operator Support Equipment

The requirements for seats, back rests, etc., will depend both on the period of operation involved and on the physical features of the workplace (space availability, console configuration, etc.). This subsection provides guidelines for the design of operator support equipment for both short-term (i.e., under 30 min.) and long-term (e.g., over 30 min.) operations.

4.1 Seats

The main consideration in seat design is to provide some body stabilization so that the operator can carry out his task effectively. For long-term operation, a second consideration is imposed: the minimization of fatigue.

A fundamental principle of seat design applicable to long-term operation is that the operator must be able to change his position from time to time. Hence, seats must be designed in such a manner that the body is not confined to a single position but is allowed to assume any of several positions.

* Seat designs recommended for both long- and short-term operations are illustrated in Figures 3-61 and 3-62.

  a. Seat height (i.e., the distance from the seat to the floor when a person is seated with his feet placed squarely on the floor and his knees at right angles) should be 17 in. + 1 in. and — 2 in. (1 in. steps) to accommodate 95% of potential users. Seats that are adjustable in height should be used for both long- and short-term operations.

  b. Seat length (i.e., the distance from the back of the seat, or buttocks, to the back of the leg just below the knee, or popliteal area, when the individual is sitting erect with his feet placed squarely on the floor) is dependent upon the configuration to be used. For other than circular seats, a seat length of 17 in. in adaptable to the majority of potential users. For circular seats, the diameter can be reduced to 15 in.

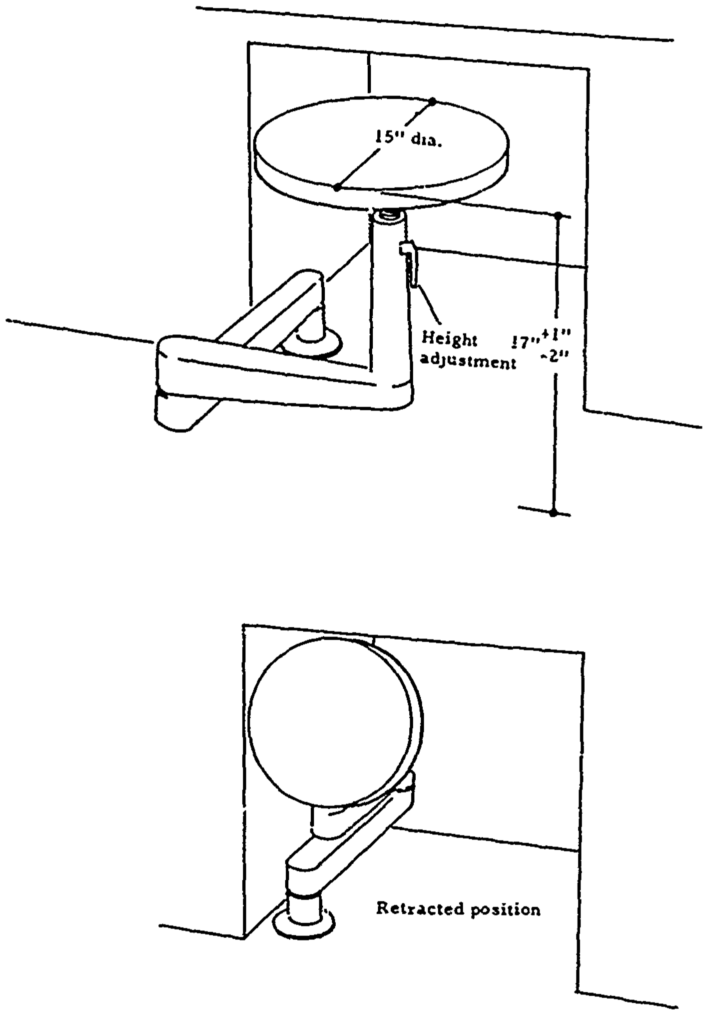

Fig. 3-61. Fold-away seat for short-term operations.

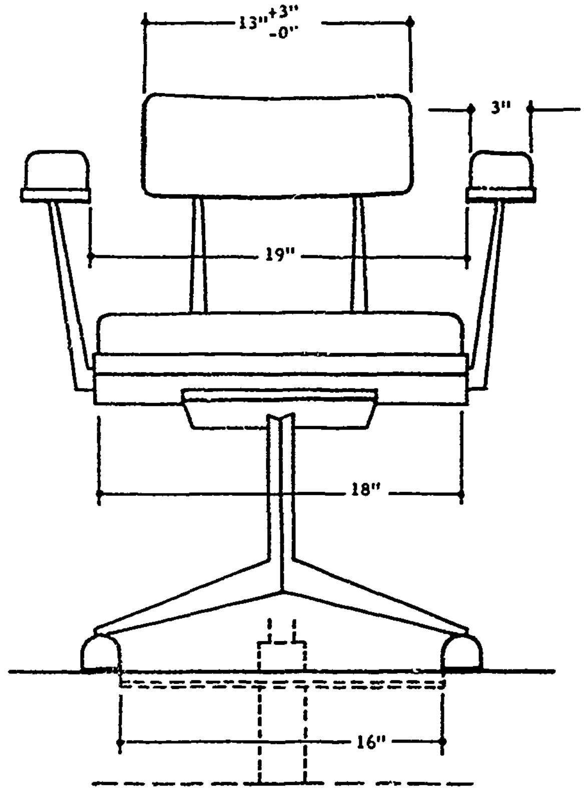

Fig. 3-62. Seat for long-term operations.

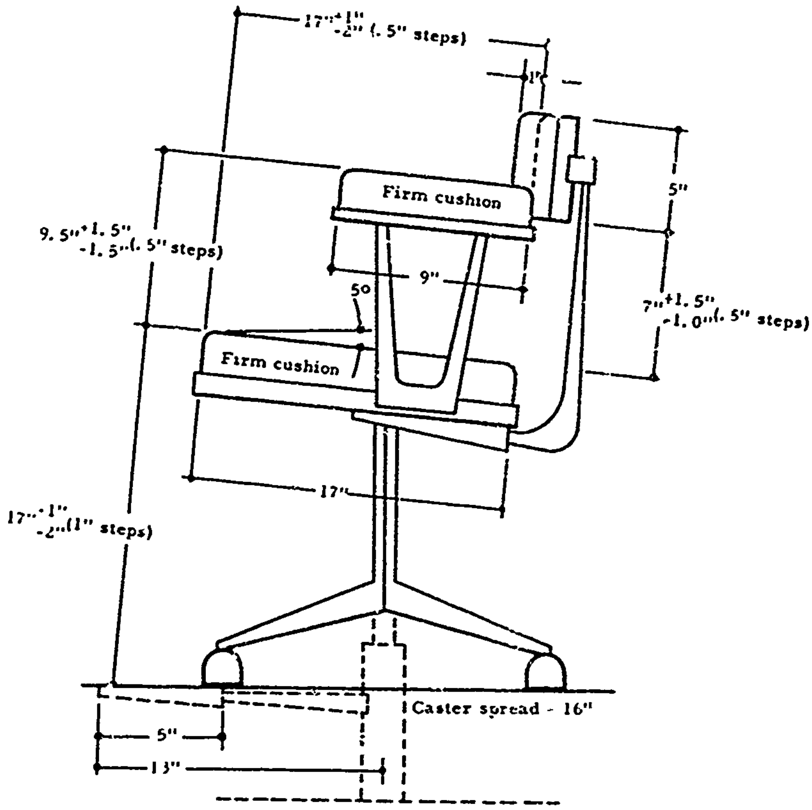

Fig. 3-62 (Continued)

c. Seat width is not as critical a dimension as is seat length, principally because a wide seat will not cause detrimental physiological effects. Hence, a seat width of 18 in. is adapted to the measurements of large-proportioned individuals.

4.2 Arm and Foot Rests

* The arm rest is a comfort feature that should be incorporated when operators are required to sit for extended periods of time.

a. Height of arm rests should be 9.5 in. (adjustable as shown in Fig. 3-62) above normal seat height (seat compressed), based upon the measurement of elbow height given in Figure 3-44.

b. Width of arm rests should be at least 1.5 in. (3 in. preferred as shown in Fig. 3-62).

c. If the console or panel has a tracking control, the operator's arm should be supported in such a manner that it lies in the same plane as the control. Support can be provided either by the panel itself or by a special arm rest in an arrangement that supports the operator's arm without need for him to raise or depress his shoulder.

* Foot rests should be incorporated in either seat or console design for workplaces to be used during periods of extended operation. Foot rests provide greater stabilization for the body. The height of foot rests with respect to the floor should be determined by the height of the work surface. It should be adjustable by ±4 in.

4.3 Back Rests

* Back rests should be provided for seated operators who are required to remain at their stations for long periods of time. The area of the back that is subject to the greatest strain and hence the most important area for which support must be designed is the lumbar region of the spine. A

well-designed back rest should also provide for changeability of back position, and ideally, the more support area provided by a back rest, the greater the ability to alter one's position. However, if space limitations are critical, a back rest that supports only the lumbar region will suffice; such a support should be designed with sufficient space below it to permit the operator to sit back far enough to arch the small of his back slightly and thereby reduce fatigue by altering the posture of the back.

* The height of the back rest should be at least 5 in., starting from a point approximately 7 in. above the seat, adjustable + 1.5 in. and – 1.0 in.

* Width of the back rest should be approximately 13 in. +3 in. and – 0 in. in order to accommodate the requirements of 95% of the population. For unrestricted elbow movement, the 13 in. width is preferred.

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CONTENTS OF SECTION

This section of the handbook[+] contains a discussion of maintainability concepts and human factors guidelines to be used in the design of FBM equipment. Maintainability is "a quality of the combined features and characteristics (equipment design, job aids, and job support) of a system which facilitates the rapidity, economy, ease and accuracy with which maintenance operations can be performed and the system thus kept in or returned to operating condition, by average naval technicians, under the environmental conditions in which the system will be maintained."[++] Improvement in equipment maintainability is characterized by a reduction in the down time associated with that equipment.

All FBM subsystems must function at a level which permits a high state of weapon system readiness reliability over prolonged patrol periods. FBM ships must have a self-sufficient maintenance capability. To operate effectively during long periods of isolation, this, in turn, is based on careful planning for such support requirements as spare parts, tools, test equipment, manuals, and the number of technicians at various levels of competence (as assured by selection and training). The extent to which these maintainability and support requirements are predetermined by basic equipment and system design[+++] factors must be recognized. It is important for future FBM ships that the equipment designer realize that the relatively minor design decisions which he makes with regard to such typical design factors as chassis layout, modularization, location of test points, color or other types of equipment coding, and mechanical or structural design features can seriously affect both FBM system readiness reliability and maintenance capability.

The relative sensitivity of each specific design factor to a quantitative measure of maintainability (down time) must also be taken into account, particularly where trade-offs are involved.[++++]

[+] Original issue July 1960; revised, August 1962.

[++] After Rigby et al[(33)].

[+++] See Volume 1, Section 2 for a discussion of the guiding philosophies and concepts which must be properly established in the early phases of system development.

[++++] Specific guidelines for design have been rated in terms of sensitivity to assist the user in making trade-off decisions.

Contents

The objectives of this section are:

a. To demonstrate the importance of reducing equipment down time.

b. To identify the elements of which down time is composed.

c. To describe the design factors which influence each element of down time.

d. To trace the relative importance of these design factors with respect to other engineering and system design areas.

e. To provide design guidelines based on the above.

Taken together, this material will provide a logical basis for design of equipment for maintainability.

This section contains three major subsections which will be described briefly at the outset.

I. Analysis of Down Time

This subsection defines down time as the quantitative measure of maintainability. The significance of down time is explained by the use of a specific example of navigation equipment. This example shows how both individual equipment availability and system readiness-reliability will be affected by changes in either reliability or maintainability. This means that the equipment manufacturer actually has a certain leeway in design and he should use this leeway to aim at an optimum solution to a specific design problem.

Equipment becomes unavailable for use (i. e., is "down") for many reasons, among which may be mentioned (1) failure detection, (2) waiting for technicians, (3) fault localization, (4) waiting for spare parts, (5) being repaired, (6) being checked out, (7) preventive maintenance, etc. Most of the factors which contribute to down time are under either the direct or indirect control of the equipment designer, who has at his disposal many techniques or design variables which he can employ to adjust the down time parameter. Each design technique will affect equipment availability for operational use in different ways. These effects must be understood before intelligent design practices for future FBM ships can be established. Examples of how equipment down time can be reduced effectively by "designing for maintainability" are discussed. The elements of corrective maintenance are identified. There is a brief treatment of the various approaches to the reduction of down time. Factual data are presented to show

the relationship between the most complex down time element, fault localization time, and several other pertinent variables.

II. Guidelines for Design of Equipment for Maintainability

Important design factors (e. g. , test equipment, tools, weight, handles, accessibility, openings, functional packaging, modular design, mounting of components, etc.) have been identified and specific guidelines developed for each category. An evaluative rating is attached to each guideline to indicate: (1) its relative sensitivity or importance (i.e., the extent to which down time can be reduced by incorporating the recommended design feature); (2) its effect on available equipment volume; (3) its effect on equipment cost; and (4) its effect on equipment failure rate. These evaluation factors and the rating code used are described in detail on page 256.

The guidelines included in this section have been preselected and limited to those which will reduce down time sufficiently to offset any design penalty which may result in terms of increased volume, increased cost, and/or increased failure rate.

III. Side Effects of Design for Maintainability

In conclusion, possible trade-offs related to any specific design activity and some of the side effects, both positive and negative, resulting from maintainability design are discussed.

The design of equipment for maintainability cannot be considered in isolation from the other aspects of design which must be undertaken at this time. These include: the design of equipment for operation (i. e. , for the operator rather than the maintenance technician), the development of maintenance procedures, the control of environment, and the selection and training of personnel.

The use of human factors specialists to assist in the application of this section of the handbook is desirable. Since many compromises must be made throughout the design cycle, such specialists should be available to assist the design engineers in recommending or evaluating any "trade-offs" which may be required among human factors, engineering, equipment or component availability, or the many other factors which ultimately determine the design of the system and its individual pieces of equipment. This handbook provides human factors guidelines which can be used both by the human factors specialists and by the design engineer. However, it cannot, by itself, insure the judicious application of these guidelines to the specific design situation.

I. ANALYSIS OF DOWN TIME

1. Down Time: The Quantitative Measure of Maintainability

Two basically different kinds of down time must be defined: scheduled and unscheduled. Scheduled down time does not involve equipment failure. It is required for certain equipment types that scheduled time be allotted for routine servicing, preventive maintenance, and periodic checkout functions. Unscheduled down time, on the other hand, is associated with equipment failure and involves corrective maintenance in some form.

With the exception of a few ship control, navigation, and other functions which require continuous operation over the duration of a mission, most preventive maintenance, routine servicing, and checkout functions can be scheduled for periods when the equipment is not in demand. Thus, since these functions can always be planned ahead of time, they will not be considered in detail in this section. Instead, the primary concern will be for unscheduled down time involving corrective maintenance.

Unscheduled down time is defined as the length of time in hours (measured from the time of occurrence of component degradation or failure) that a device is unable to provide a specified level of performance. It is the time between the occurrence of a failure in a device and the subsequent return of that device to satisfactory operating status. Before going on to establish a basis for down time reduction through design for maintainability, it is instructive to determine the importance of down time to the operational FBM system and the elements of which it is comprised.

2 The Significance of Down Time

2.1 An Example

As an illustration of the down time relationships involved in maintenance, it is instructive to examine a particular example. The SSB(N) 598 contains three identical inertial navigators whose function it is to provide continuous, accurate, and reliable navigation data for maneuvering and for missile guidance purposes. For illustration, it will be assumed that an inertial navigator has the following characteristics:

a. Exponential distribution of operating time between failures.

b. Exponential distribution of down time.[+]

c. Normally requires reset (by external position fix) every "T" hours.

d. One maintenance technician (plus one apprentice) is sufficient to handle a failure.

Let us now define the following terms:

T_f = mean operating time between failures (in hours)

T_d = mean down time

ρ = T_d/T_f (note that this is a primary design parameter of the device)

T = normal period between resets (in hours)

P_n = probability that exactly "n" inertial navigators will be "down" at any randomly selected time

N = number of inertial navigators (=3 in this example)

M = number of trained maintenance technicians continuously on for maintenance of the inertial navigators

A = availability, or probability that a particular inertial navigator is operable at a randomly selected time

R = readiness reliability, or probability that at least one out of three inertial navigators is operable at any randomly selected time.

Equipment availability is given by the expression:

$$A = \frac{T_f}{T_d + T_f} = \frac{1}{1 + \rho} \tag{1}$$

[+]This is an approximation used for purpose of example. It is known that down time is distributed log normally rather than exponentially, but the mathematical derivations using the former are overly complex for inclusion here. The geometric mean, rather than the usual arithmetic mean, is more meaningful for log normal distributions.

Availability is plotted against ρ in Figure 4-1. It is of primary significance for one-of-a-kind equipment, such as the Type 11 periscope. Readiness reliability is of importance in discussing redundant or parallel systems such as 3-SINS, 2-NAVDAC, 16-missiles, etc. In order to obtain a plot of R similar to that for A in Figure 4-1, we first note that:

$$\frac{P_n}{P_0} = \left\{ \begin{array}{ll} \dfrac{N!\,\rho^n}{(N-n)!\,n!}, & n \leq M \\ \dfrac{N!\,\rho^n}{(N-n)!\,M!\,M^{n-M}}, & n \geq M \end{array} \right\} \quad 0 \leq n \leq N \tag{2}$$

$$\frac{1}{P_0} = \sum_{n=0}^{N} \left(\frac{P_n}{P_0}\right) \tag{3}$$

$$P_n = \left(\frac{P_n}{P_0}\right) P_0 \tag{4}$$

The foregoing equations (2, 3, and 4) are derived from finite queueing theory. Using the equations and definitions presented herein, we find for the 3-SINS system example that system readiness reliability R is given by:

$$\begin{aligned} R &= (P_0 + P_1 + P_2) \\ &= (1 - P_3), \text{ since } \sum_{n=0}^{N} P_n = 1 \end{aligned}$$

Readiness reliability for the 3-SINS subsystem is plotted against ρ for one, two, and three technicians in Figure 4-2.

For the NAVDAC case, $N = 2$ and $R = 1 - P_2$. For the case of 16 missiles, $N = 16$, and at least 14 must be ready to fire within "X" minutes. Thus, not more than two can be down, and therefore $R = (P_0 + P_1 + P_2)$, i.e., probability that two or less are down. This method applies as well to missile components such as guidance capsules, flight control subsystems, etc. Curves similar to those in Figure 4-2 can be derived from Equations (2) through (4) for any of these cases.

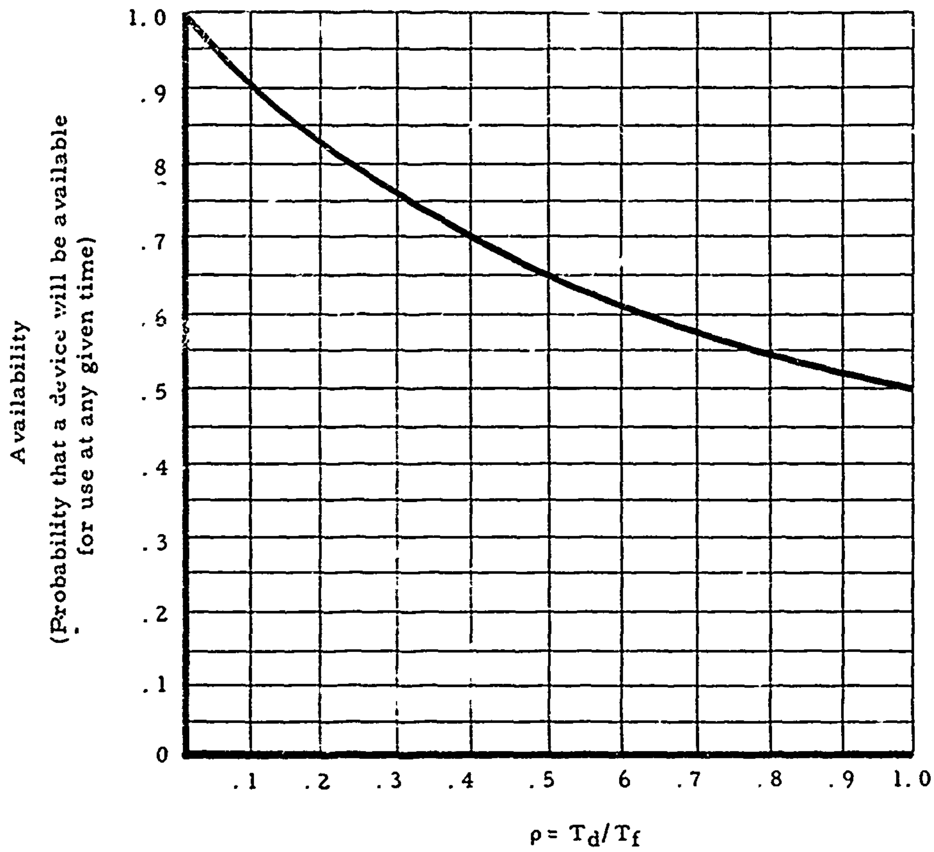


Fig. 4-1. Relationship of equipment available to down time and failure rate. (For this example, exponential failure rate and down time are assumed.)

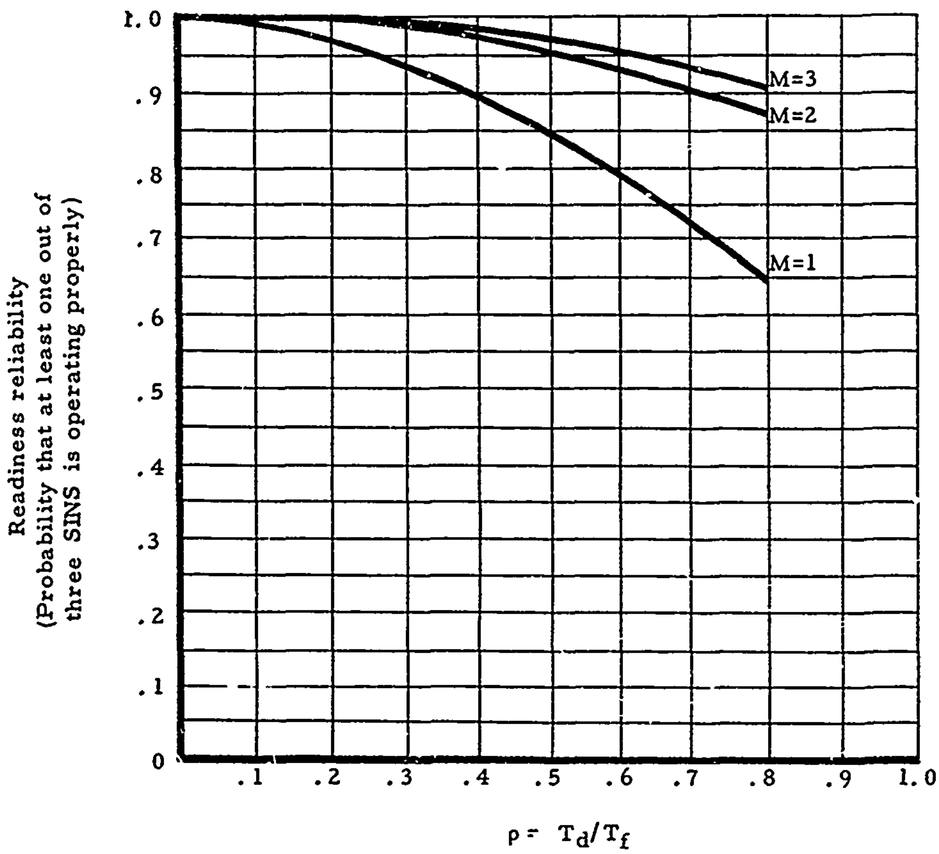


Fig. 4-2. Relationship among readiness reliability, down time, failure rate, and number of technicians. (For this example, exponential failure rate and down time are assumed.)

The design parameter ρ obviously is of particular importance. By definition, $\rho = T_d / T_f$. This means that the design parameter ρ is composed of two components in "equal measure·

a. Reliability, as measured by mean time between failures, (T_f); and

b Maintainability, as measured by mean down time (T_d).

Obviously, both individual equipment availability and system readiness reliability will be affected by changes in either T_f or T_d. The important thing to note there is that, within limits, a linear trade-off exists between reliability and maintainability.

These limits are determined by other factors. For example, suppose a readiness reliability of 0.99 is required for the 3-SINS system during the continuous operating period T between resets. From Figure 4-2 this requirement corresponds to $\rho = 0.1$ for a minimum manpower situation (one technician on call). Quite obviously, the required value can be obtained with an infinite number of appropriate combinations of T_f and T_d.

Suppose, however, that an additional set of constraints is imposed:

a. Probability of failure of an inertial navigator during the period T between resets must be less than 0.1. (If T = 10 hours, this requires immediately that the mean operating time between failures (T_f) be 100 hours or greater +)

+In general, $P(T) = 1 - e^{-T/T_f}$

$P(X) = e^{-X/T_d}$

If $P(T) \leq 0.1$ and $T = 10$ hours, then solving for T_f results in $T_f \geq 100$ hours

If $P(X) \leq 0.1$ and $X = 7$ hours, then solving for T_d results in $T_d \leq 4$ hours

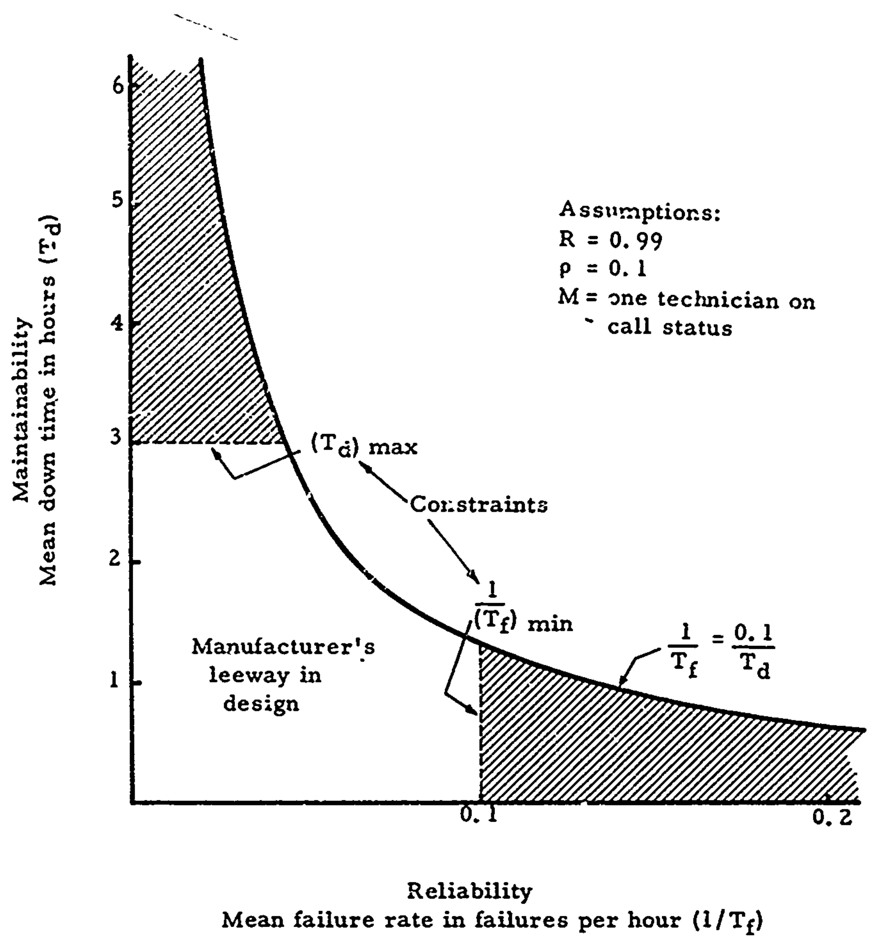


Fig. 4-3. Specification of equipment availability. (Illustration of trade-off between maintainability and reliability to achieve a given level of over-all system availability.)

b. Probability of a repair not being completed within X hours must be less than 0.1. (If, for example, X = 7 hours, then the mean down time (T_d) must be limited to 3 hours or less. +)

Establishment of these two constraints (in this example, T_d maximum = 3 hours and T_f minimum = 100 hours) and the probabilities associated with them should be based solely upon operational considerations. When combined with the availability requirement, they represent reliability and maintainability design goals for the device.

These goals can now be specified to a manufacturer. Figure 4-3 is a plot of T_d versus $(1/T_f)$ for $\rho = 0.1$, corresponding to a 3-SINS system readiness reliability of R = 0.99 with one technician on call. The two operational constraints, (T_d) maximum and (T_f) minimum, are also shown.

Using the techniques embodied in Figure 4-3, it is possible to specify both reliability and maintainability design goals in such a manner as to allow the manufacturer leeway in balancing one against the other to minimize system cost. This can be done without fear of compromising the readiness reliability requirements for the equipment, since they are already taken into account in the specification.

3. Importance of Reducing Down Time

An idea of the importance of reducing down time may be obtained from a brief review of Figures 4-1, 4-2, and 4-3. Figure 4-1 indicated the effect of down time upon individual equipment availability. If mean time between failures (T_f) is 100 hours, then the horizontal scale represents mean down time in fractions of 100 hours. For example, to meet an equipment availability requirement of .95 with T_f = 100 hours, mean down time (T_d) must not exceed 6 hours, according to Figure 4-1. This kind of requirement can only be met through adequate design, as will be demonstrated.

As previously mentioned, readiness reliability is a more appropriate measure than equipment availability when dealing with multiple systems having several identical devices (e. g., 3 SINS, 2 NAVDAC, 16 missiles), and a limited number of repair technicians (in general, when number of equipments exceeds number of technicians).

+See footnote on page 233.

Figure 4-2 indicated the effect of down time upon subsystem readiness reliability for the example of three identical equipments operating in parallel (e.g., 3 SINS). It also indicated the critical interaction between down time and manpower requirements. For example, suppose that readiness reliability of .95 is required. Furthermore, again assume that $T_f = 100$ hours. Then, according to Figure 4-2, if $T_d \approx 55$ hours, three trained technicians will be required to be on call at all times. If T_d is reduced to about 28 hours through application of maintainability design techniques, then only one trained technician will be needed. Thus, a 50% reduction in down time results in a 67% reduction in manpower requirements for this particular example. The savings are much more pronounced where a larger number of identical devices (e.g., guidance capsules) must be maintained in a constant state of readiness. (Note that reducing down time involves only a one-time design cost, whereas reducing manpower requirements saves money many times over in terms of immediate manpower needs, training, shipboard space, and turnover of military personnel.)

Finally, Figure 4-3 summarized the kind of information which can be derived from such analyses for use in development and production specifications. Proper interpretation of Figure 4-3 is that the manufacturer is permitted complete freedom within the unshaded area in designing his equipment to meet the specified availability or readiness reliability requirement, whichever is appropriate. Note that moving in toward the origin along either axis in Figure 4-3 will be costly (i. e., reducing either failure rate or down time will cost money); nevertheless, this type of specification allows the manufacturer to trade off reliability for maintainability in such a manner as to minimize total cost.

It must be remembered that the cost of reliability design is primarily the cost of reliability assurance. This requires careful testing, often to destruction, of components and subsystems under controlled conditions. The cost of such tests in both dollars and time is very great (e. g., the largest part of the cost of any missile development program is for assuring a given level of reliability). For this reason alone, it is important that every possible leeway be given to a manufacturer in terms of reducing reliability while at the same time maintaining some desired level of equipment availability or of subsystem readiness reliability, whichever is the appropriate measure. The cost of a compensatory reduction in down time through proper design, on the other hand, will, in most instances, be negligible when compared to the cost of an equivalent reduction in failure rate.

4. Elements of Down Time

The characteristic mean duration of equipment down time in hours over a large sample of failures and repair is defined as T_d. Let us now define the particular duration of equipment down time following any given failure as t_d. In general, it is composed of the following time elements, in the sequence given:

$$t_d = t_{fd} + t_{wm} + t_{fv} + t_{ap} + t_{fl} + t_{ws} + t_{fc} + t_{aa} + t_{co},$$

where

t_{fd} = time in hours between failure occurrence and failure detection

t_{wm} = time in hours between failure detection and arrival of maintenance technician

t_{fv} = time in hours for verification of failure

t_{ap} = access and preparation time in hours (i. e., time between arrival of maintenance technician and initiation of fault localization procedure)

t_{fl} = fault localization time in hours (i. e., time required to localize source of failure to a replaceable or repairable module)

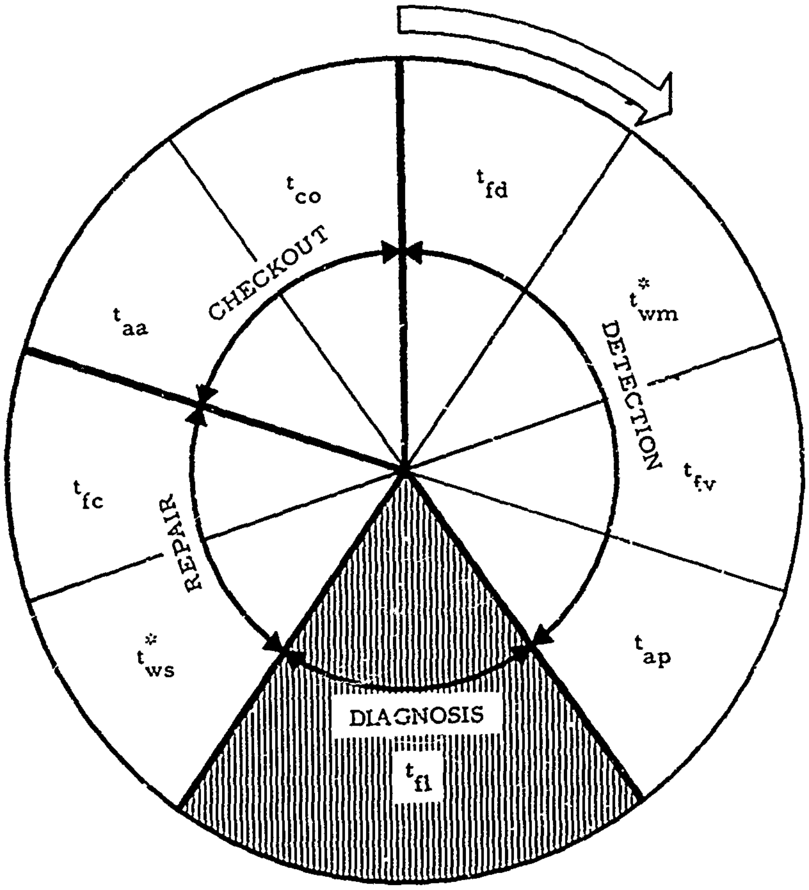
t_{ws} = time in hours between localization of failure source and arrival of needed spare module or spare part

t_{fc} = fault correction time in hours (i. e., time required to repair or replace faulty module)

t_{aa} = alignment and adjustment time in hours

t_{co} = checkout time in hours (i. e., time required to verify that equipment is again operating properly)

Not all elements are likely to be involved in any given failure occurrence; nevertheless, each must be reckoned with in accordance with the extent of its contribution to over-all down time. Each element of down time is described in detail in the following sections. (Fig. 4-4)



*These elements are not directly controllable by equipment design.

Fig. 4-4. Elements of down time in the corrective maintenance process.

4.1 Failure Detection (t_{fd})

The time between the actual occurrence of a failure (either catastrophic or degradation) and its cognition by a human operator is defined as failure detection time (t_{fd}). This time period can be extensive in two major instances:

a. If rate of degradation is slow, system operation may be compromised long before failure or degradation is actually detected.

   Example: Radar, which obeys an inverse 4th power law of radiation, can exhibit substantial losses in operating distance (50%) for smaller degradations in transmitted power (16%).

b. If the equipment is permitted to lie dormant between checks. A degradation or failure occurring during this period will obviously go unnoticed until it is discovered during the next scheduled checkout.

4.2 Waiting for Technicians (t_{wm})

In most FBM applications, a single maintenance technician may be trained to maintain as many as a dozen different kinds of devices. The likelihood that a repair cannot be started immediately after failure detection due to unavailability of a maintenance technician will depend directly on four factors:

a. Number of devices
b. Failure rate per device
c. Number of technicians trained on the devices in question
d. Repair time per device.

4.3 Fault Verification (t_{fv})

In most cases, the existence of a failure is detected by the equipment operator either during the course of normal operation or during equipment checkout. The first task of the maintenance technician upon arrival on the scene is to verify that a failure has indeed occurred and that the equipment is, in fact, not operating properly. This may require special procedures.

4.4 Access and Preparation (t_{ap})

Once the existence of the failure is verified, preparation for troubleshooting can begin. Three important areas of maintenance activity are involved here:

a. Assembling appropriate manuals, drawings, etc.
b. Assembling appropriate test equipment and tools
c. Gaining access to the equipment.

4.5 Fault Localization (t_{fl})

This phase involves the actual troubleshooting or diagnostic procedure required to isolate and identify the failed component. It requires:

a. Data gathering
b. Data interpretation
c. Decision.

The troubleshooting procedure can be conceived as a sequence of such decisions which, if made on a logical and systematic basis, serve to narrow the alternatives in an efficient manner until the trouble source is finally isolated. It should be noted, however, that each such troubleshooting decision takes a finite amount of time, most of which is involved in the data gathering stage. The latter may further be subdivided as follows:

a. Manual and instruction reading
b. Circuit diagram tracing
c. Searching and location of test points on chassis
d. Test equipment manipulation
e. Prime equipment manipulation
f. Indicator reading.

4.6 Waiting for Spare Parts (t_{ws})

Before the faulty component can be replaced, a spare component must be obtained from the supply inventory. This may take anywhere from minutes to months, depending upon whether the needed spare is available within the submarine, from the tender, or from the depot. Waiting time will depend primarily upon transportation time, i.e., time required for transfer of a spare part from supply inventory to equipment site. The probability of having to wait, on the other hand, will depend upon parts failure rates and inventory levels.

4.7 Fault Correction (t_{fc})

Once the source of trouble is isolated, the faulty component must either be repaired or replaced. The general maintenance philosophy for the

FBM system is one of replacement only. However, there will always be problems involving bent connectors, broken leads, short circuits, and similar failures where shipboard repair will be mandatory. Thus, both repair and replacement must be covered.

4.8 Alignment and Adjustment (t_{aa})

Many types of "degradation failures" can be ascribed to slow changes in circuit characteristics which very often can be corrected by appropriate alignment or adjustment of variable circuit parameters. For example, a frequency drift in the Time and Frequency Standard can be corrected periodically by adjustment of its oscillator frequency to conform with the WWV or Draco standard frequency signals. In addition, although it is undesirable and frowned upon from a design standpoint, module or component replacement may, through inadequate circuit design, entail alignment or adjustment of variable circuit parameters as a necessary part of the replacement installation. Finally, design factors associated with mechanical alignment and adjustment, as with the keying of multiple connectors, must be considered.

4.9 Checkout (t_{co})

Once a fault has been corrected, the system must be tested to insure that it is indeed operating within tolerance. This will ordinarily involve certain checkout procedures and may require special test equipment. Time will be consumed mainly in the carrying out of the checkout procedure. Again, the latter will involve:

a. Assembling appropriate test equipment
b. Assembling appropriate manuals, drawings, etc.
c. Manual and instruction reading
d. Searching and location of test points on chassis
e. Test equipment manipulation
f. Prime equipment manipulation
g. Indicator reading
h. Comparison with tolerance limits
i. Decision

The relationship between the factors discussed to this point is illustrated in Figure 4-5.

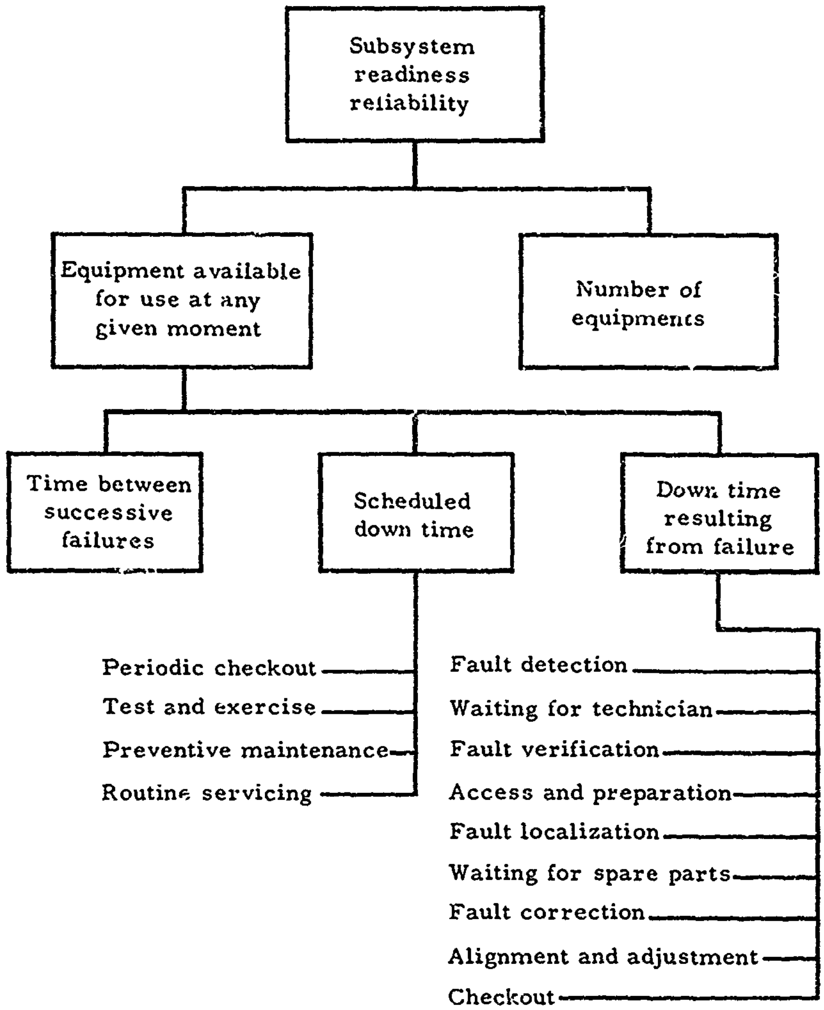


Fig. 4-5. Important variables affecting maintainability and their relationships.

5. Approaches to the Reduction of Down Time

Since the down time associated with any failure is the sum of the times required to complete each of the independent down time elements relevant to that failure, it is obvious that the only ways to reduce down time are: (1) to reduce the time required per element; and/or (2) to reduce the number of elements required to correct a given failure. If we examine the elements described in the previous paragraph, we find three groups: some elements which are tied to logistic and support considerations (i. e. , waiting for technicians, waiting for spares); others which are joint functions of equipment design and personnel training parameters (i. e. , fault localization, fault correction, alignment and adjustment); and a third group which includes those elements affected primarily by equipment design features (i. e. , detection, verification, access and preparation, and checkout).

The emphasis of this document is on equipment design and, therefore, it will stress design features which can serve to reduce the time associated with each element in the latter two groups (or to eliminate the need for that element in a given instance). Table 4-1 summarizes the relationships between design features and corrective maintenance elements. Specific design recommendations affecting each element will be found under the appropriate headings in Guidelines, page 255 ff. The remainder of this section will be devoted to a more general discussion of each element and the design features relating to it.

It is possible to go to the extreme of designing a system which employs redundant or stand-by equipment and provides for automatic fault detection, localization, and insertion of the entire stand-by unit. Such an approach may have merit in the case of systems requiring continuous "perfect" operation, but it merely postpones the maintenance function and therefore cannot be considered as a general solution for maintainability design.

5.1 Reducing Detection and Verification Time (t_{fd})

The extent of the time lag between the occurrence of a failure and its detection by the maintenance technician is primarily a function of the following factors:

a. The nature of the failure (catastrophic or gradual) and its functional effect upon the system.

b. The extent to which the affected output is monitored (including automatic, period, and marginal performance monitoring).

Table 4-1

Design Features and the Elements of Down Time Which They Affect[+]

Design Features	Detect Failure	Verify Failure	Access	Trouble-shoot	Spare Parts	Correct Fault	Align & Adjust	Checkout
Manuals and Procedures	X	X	X	X		X	X	X
Failure Indication	X	X		X				
Test Equipment	X	X	X	X			X	X
Test Points		X	X	X			X	X
Tools			X	X		X	X	X
Weight			X			X		
Handles			X					
Covers, Cases Doors			X					
Accessibility			X	X		X	X	X
Openings			X					
Modular Design			X	X	X	X	X	X
Standardization				X	X			
Controls							X	
Mounting of Components			X	X		X	X	
Labeling and Coding			X	X	X	X	X	X
Cabling and Wiring			X	X		X		
Lubrication						X		
Connectors			X	X		X		
Fuses and Circuit Breakers	X			X		X		
Safety			X	X		X	X	X

[+]Section 3 contains guidelines for the selection and design of displays which are also applicable to maintenance displays.

c. The location and adequacy of the display used to provide failure indications to the operator.

The elapsed time interval can be reduced by focusing on the last two factors. The general design features which would reduce t_{id} include:

a. Provision for automatic monitoring and alarm for critical equipment parameters (internal signals as well as outputs). This is especially important for those failures which are not immediately obvious to an operator (e. g. , in the case of a radar or sonar, a loss in range sensitivity due to output power reduction is often not readily obvious to the observer).

b. Provision for continuous or periodic marginal checkout of those portions of the equipment likely to exhibit gradual degradation. These should be internal wherever possible and generate an alarm only if the values or the rates of change are outside of stated tolerances.

c. Design and location of failure and status indicators and alarms in accordance with the human engineering recommendations set forth in Section 3: Displays, I.

5.2 Reducing Access and Preparation Time (t_{ap})

The time interval associated with these elements is devoted largely to physical actions on the part of the technician. These consist of: (1) gaining access to the faulty rack, cabinet, or subsystem; (2) obtaining the necessary manuals, references, and job aids, and locating the relevant portions of these documents; and (3) assembling and readying the necessary tools and test equipment.

A reduction in the time spent on these operations can be achieved by following the specific recommendations in the relevant areas indicated in Table 4-1 and by design of test equipment panels and workspace layouts in accordance with Section 3; Panels and Consoles, IV.

5.3 Reducing Fault Localization Time (t_{fl})

Fault localization (troubleshooting) is the most complex and time consuming element in the corrective maintenance process and is therefore discussed here in greater detail. It requires more skill and knowledge on the part of the

technician and often consumes as much as 50% of the total down time for a given failure.(21)+ The time spent in localizing a failure to the level of a repairable/replaceable unit is a complex function of equipment design and technician skill, but, in spite of its obvious importance, the relationship between design and ease of troubleshooting has not yet been fully explored. Improved design can reduce the difficulty of the localization process in two ways: it can reduce the time requirement directly, and it can simplify (and shorten) the training prerequisites for effective troubleshooting performance.

The inherent complexity and the need for testing in the fault localization process can be explained as follows: Whereas a given component failure will always result in the same symptom, the reverse is not true. The same symptom can often be caused by a number of possible component failures. If the same symptom were always caused by a specific component failure, there would be no need for testing, since the technician could be trained to use a simple symptom-failure analysis technique.

While it is theoretically possible to perform fault localization automatically or, alternatively, to eliminate completely the localization element from the maintenance process by providing malfunction indicators at the level of a repairable/replaceable unit, such constraints as size, circuit complexity, and cost prevent the widespread use of these techniques on operational equipments. The design engineer is thus faced with the problem of how best to design equipment for rapid and efficient fault localization. Unfortunately, the data necessary for the solution of this problem are not yet available in sufficient quantity and detail to permit a complete list of design recommendations specific to this element. Nonetheless, recommendations relating to maintenance manuals and troubleshooting guides can be set forth; these are included in the Guidelines, pages 259-265.

The time spent in isolating a malfunction can be divided into two components: (1) the time required for the logical processes involved in selecting a strategy and a sequence of tests and in evaluating the resulting data, and (2) the time required for the physical activities involved in making these checks.

The time consumed in logical decision making can be reduced by:

a. The use of automatic or semi-automatic fault isolation techniques.

+See McKendry et al (21), Supplement II: Survey Information.

b. Provision of detailed step-by-step troubleshooting guides and procedures.

c. The use of a modularization and packaging technique which provides the technician with a recognizable sequence of checks and the greatest possible amount of information per check.

d. The design of displays which permit unambiguous interpretation of test results.+

Physical activity time can be reduced by means of the following features:

a. Provision for easy access (sufficient space and a minimum of covers, latches, etc.) to components or modules which must be tested directly, and coding of these units for ease of location and identification.

b. Use of remoted test points which are centrally located, easily accessible, and coded for ease of identification and interpretation.

The relative emphasis to be placed on reduction of these two components should be based on analyses conducted during the early phases of the program. If the troubleshooting task is likely to be such that the number of false or unnecessary checks is large, then the prime emphasis should be on those approaches to design and troubleshooting which will reduce the average number of checks required to isolate a failure. On the other hand, if relatively few such extraneous checks are anticipated, or if the isolation process will be straightforward, a greater pay-off will result from a reduction in the time required per check.

This can be made clear by means of the following example: Let us take an equipment consisting of 64 component parts in a simple series chain. If we assume that each part has an equal probability of failing and that each check requires 3 minutes, a totally random process would result in an average localization time of 96 minutes (32 x 3). Any "good" logic or strategy employed by the technician should reduce this time, but since the total amount of information in the system is 6 bits ($2^6 = 64$), the average time will probably not fall below 18 minutes, which can therefore be regarded as the level attained by an optimum strategy. If the technician's logic is fairly good, he may require 8 checks to isolate the fault and thus require 24 minutes. The total room for improvement is thus only 6 minutes (24 - 18).

+See Section 3: Displays, I.

On the other hand, if we can reduce the amount of time per step from 3 minutes to 2 minutes (e. g., by improving the use of automatic test equipment, manuals, and/or schematics, or by remoting test points to a central panel), we can improve performance by as much as 12 minutes (24 - 12) even if the technician continues to make the same number of erroneous checks.

If the number of "false" checks is large, a greater time reduction may result from training in the implementation of strategies than from reductions in activity times. The goal is naturally an improvement in both of these time components, but the relative pay-offs to be anticipated will differ, as shown in the preceding discussion.

The results of two investigations into the effects upon localization of various design configurations and features will serve to indicate the range of improvement that can be expected from such techniques.

The first study(12) determined the effects of a simple equipment coding technique upon fault localization time. Two similar oscilloscopes were used in this experiment. The only difference between them was that the upper chassis surface on one was coded to differentiate functional groupings of components by color (e. g., power supply groupings are contained within the red area on the chassis) and to indicate signal paths and test points by black lines and numbered symbols. Malfunctions of varying difficulty were deliberately introduced into the scopes, and the times required by experienced technicians to locate each malfunction were obtained.

Probability distribution functions derived from the data are shown in Figure 4-6 for both the coded and non-coded equipment. The effectiveness of coding in reducing the element of down time called fault localization time is directly evident from the 43% reduction in mean troubleshooting time (T) that resulted.

The second study(21)+ investigated the effects of four different packaging configurations upon localization time. Each of two different types of equipment (a radio receiver and a radar signal simulator) was packaged in each of four different ways. The four techniques were: (1) Standard - the packaging configuration originally employed by the manufacturer and fairly representative of current design practice. This is normally based upon a balancing of such

+See McKendry et al(21), Supplement I: An Experimental Investigation of Equipment Packaging for Ease in Maintenance.

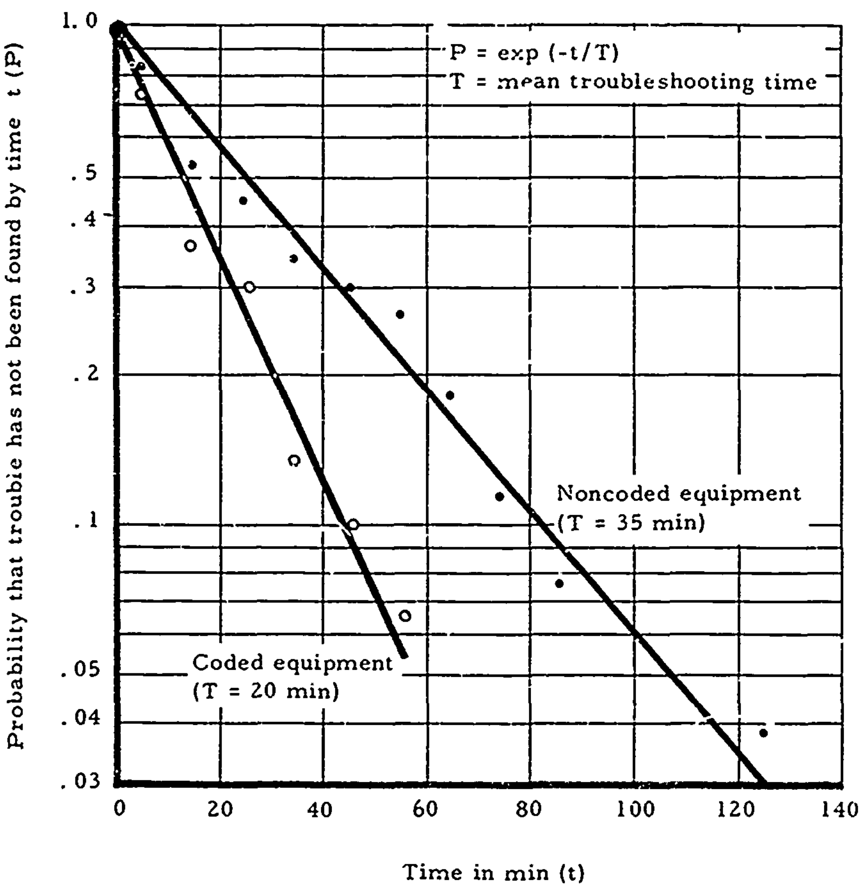


Fig. 4-6. Effect of coding a CRT oscilloscope upon troubleshooting time. (Rated Air Force technicians were used as subjects with a variety of difficult and easy troubles.)

factors as heat loss, component size and density, and weight. (2) Logical Flow - a configuration which follows the signal flow through the equipment and maximizes the division into functional blocks or modules. (3) Component Grouping - a technique which groups all components of a similar nature (i.e., resistors, transformers, capacitors, etc.) into one section of the chassis. Cheap components (e.g., condensers, resistors) were placed together on separate plug-in boards. (4) Circuit Grouping - all circuits which were functionally identical or similar were grouped, each in a separate module.

Troubleshooting times to isolate the faulty component were obtained (from a sample of experienced and inexperienced technicians) for a variety of easy and difficult malfunctions. All of the other three configurations were superior to the "standard" method, but only the comparisions between the logical flow (best) and the standard are shown on the following figures. Figure 4-7a plots the performance of inexperienced technicians on a radio receiver (one of the items of equipment used) under the best and worst conditions of packaging. Figure 4-7b diagrams the performance of experienced technicians under the same circumstances. Again, the effect of a "design technique" is apparent. There is a reduction of 27% in troubleshooting time for the inexperienced technicians and a reduction of 32% for experienced men by simply designing packaging to take advantage of logical troubleshooting and diagnostic procedures (strategies).

Figure 4-8 has been drawn to show the effect of training and experience on troubleshooting time under the "best packaging" condition. Experienced technicians took an average of 41% less time to troubleshoot than did inexperienced technicians.

The data presented above are meager, but they do indicate -- on a factual, quantitative basis -- the potential improvement in troubleshooting time, equipment availability, and reduction of system maintenance requirements that can result from a coordinated "design for maintainability" effort. In most cases, savings are feasible with small (and sometimes negligible) additional design engineering effort. It is interesting to note that the probability distribution function for fault localization appears to be well approximated, at least by visual fit, by the exponential function. Since the exponential is essentially a one-parameter function (i.e., mean = variance), any reduction in mean troubleshooting time should be accompanied by reduced variability in troubleshooting performance. The data from these and other studies show that the effects of "technician training" and "maintainability design" approaches to the maintenance problem are comparable and complementary. In fact, an optimum solution can be achieved only by attention to both design and training. The emphasis on design

engineering can be readily justified, since (unlike the continuous and costly training process), it is a one-time investment which pays dividends in terms of both reduced training requirements and improved maintenance performance.

5.4 Reducing Fault Correction Time (t_{fc})

The operations involved in fault correction consist primarily of the physical actions and manipulations required for replacement (of modules or components) or repair (of connections, wiring, etc.).+ This element is present in almost all instances of malfunction, and the time required for these actions is a direct function of the nature of the corrective operation and the following factors:

a. The degree of accessibility provided by the equipment configurations and the workspace.

b. The adequacy of maintenance manuals in terms of special instructions, location diagrams, exploded drawings, specification of required tools, etc.

c. Equipment design features pertaining to coding, instructional templates, non-reversible pin-connectors, etc.

Specific recommendations for design and maintenance manual features which will reduce correction time are presented in the pertinent sections, as indicated in Table 4-1.

5.5 Reducing Alignment, Adjustment, and Checkout Time (t_{aa}, t_{co})

Alignment and adjustment of variable parameters may sometimes be sufficient, by themselves, to correct an out-of-tolerance value (and thus constitute a corrective action), or they may be required after the completion of a corrective action which involves a particularly sensitive or matched component (or module). In the first instance, adjustment (within normal ranges) may actually be preferable to replacement or repair, since it usually requires less time and effort. (It should not normally be used simply as a means to compensate for

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+It should be noted that correction time is limited to active repair/replacement time and does not include delays due to unavailability of spare parts, manuals, or necessary tools.

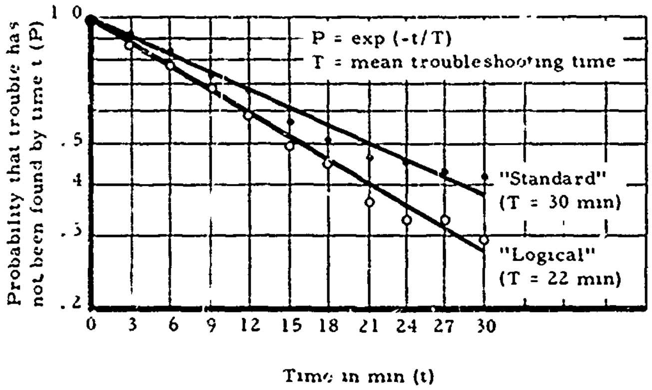


Fig. 4-7a

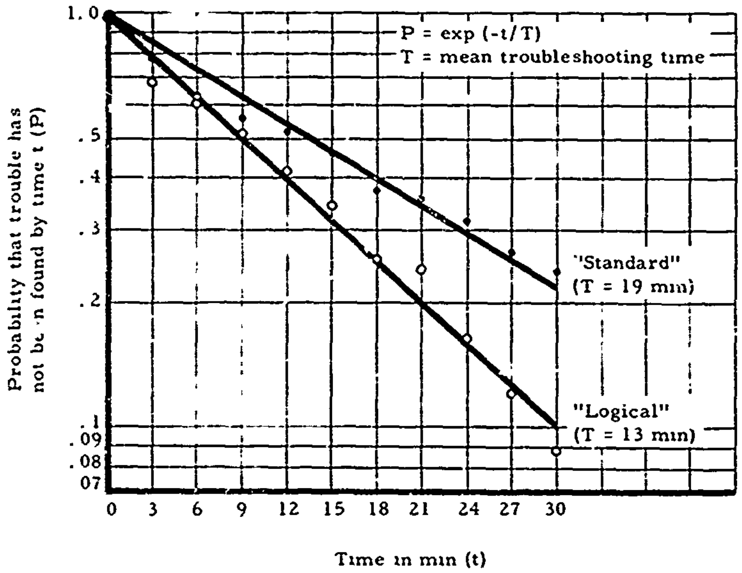


Fig. 4-7b

Fig. 4-7. Effect of "standard" vs "logical" packaging on troubleshooting time.

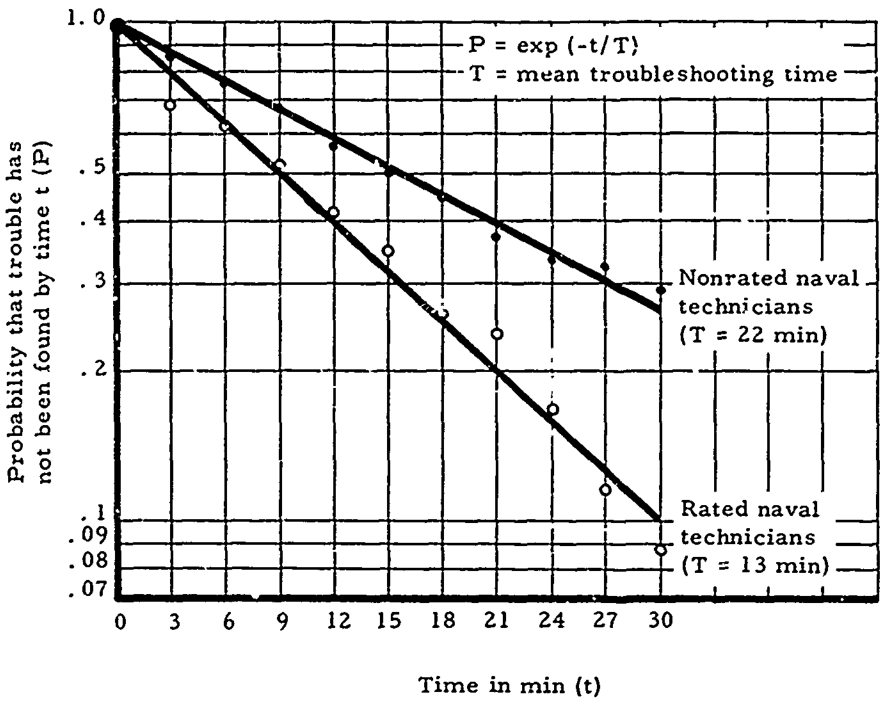


Fig. 4-8. Effect of training on troubleshooting time. (The lower curves of Figs. 4-7a and 4-7b are redrawn here to emphasize the effect of training. "Logical" packaging of radio receiver.)

known faulty components -- e.g., raising the input voltage to make up for a weak or partially defective tube. Such measures do not correct the original problem and may often cause additional failures elsewhere in the equipment.)

Wherever possible, the necessity of adjustment after a corrective action should be eliminated. The extra step involved is time consuming and adds to the total equipment down time. A saving in equipment down time can often be effected by the packaging of matched or interacting components into a single repairable module, which is replaced as a unit. (The subsequent repair and adjustment can thus be performed off-line without affecting operational down time.)

If alignment and/or adjustment are required, the time involved can be reduced by the following means:

a. Use of an adjustment control which is readily identifiable, accessible and requires no special tools for operation. (Some means should, however, be employed to prevent accidental manipulation.)

b. Use of a display device which provides the technician with appropriate information as to (1) the desired setting and tolerance limits of the adjustable variable, and (2) the direction and magnitude of his adjustments.

Checkout involves verification of the fact that the equipment has been returned to satisfactory in-tolerance operation following the corrective actions. This step will involve use of the same equipment displays or readouts which were used in the initial detection of the malfunction and may also require the use of intermediate indications such as those obtained from test points. In either instance, the general design features which serve to reduce detection and localization time will also shorten checkout time.

II. GUIDELINES FOR DESIGN OF EQUIPMENT FOR MAINTAINABILITY

1. Introduction

This section contains the design guidelines which affect each element of down time. Each guideline is evaluated with respect to:

a. Sensitivity: The extent to which down time is reduced.

b. Trade-off factors:

   1) Extra equipment space required (volume or panel area).
   2) Extra cost.
   3) Increased equipment failure rate (including difficulty in meeting environmental specifications).

These factors and the rating designations are described in detail in the following subsection.

The down time sensitivity rating attached to each design guideline reflects the author's evaluation of the extent to which down time will be reduced if the design factor is incorporated. The elements of down time which can be affected by each design factor have previously been discussed (see Figure 4-4).

In implementing each design factor, trade-offs may be required between down time reduction (the explicit goal of this section) and its affect on the three other design considerations which are acknowledged in this section: (1) volume required to implement the design factor, (2) additional cost, and (3) expected increase in equipment failure rate. The extent to which the design factor specified in the guideline affects these other design constraints has also been evaluated. The larger the rating attached to the volumetric, cost and failure rate constraints the more important is the trade-off decision, since the design penalty against the benefits gained through improved maintainability (down time reduction) are also greater.

As shown in Figure 4-3, the over-all design goal for the FBM Weapon System is equipment availability which requires both maintainability and reliability. Availability is best achieved by providing the optimum relationship between

equipment reliability and maintainability. An optimum relationship underscores the fact that, in some cases, reliability can profitably be reduced (and failure rate increased) if the end effect is to increase the over-all measure--equipment availability.

2. Rating System for Design for Maintainability Guidelines

The rating system used in this section is defined below and summarized in Table 4-2.

a. Sensitivity (s): This is defined as the extent to which down time is reduced by each design factor. Ratings are given as follows:

(3_s) "High": This rating indicates a saving, to the technician of a substantial amount of time.

(2_s) "Medium": This rating indicates a moderate saving of time to the technician.

(1_s) "Low": This rating indicates that the design factor is of convenience to the technician and/or results in saving a small amount of time.

b. Trade-Off Factors: The degree to which each design factor affects space, cost, and reliability and their respective definitions are given as follows:

1) Volume Required (v): The extent to which front panel space or equipment volume is reduced by each design factor.

(3_v) "High": This rating indicates either an addition or rearrangement of components which will most likely result in a large increase in equipment space or volumetric measurements.

(2_v) "Medium": This rating indicates either an addition or a rearrangement of components resulting in a moderate increase in volumetric requirements.

(1_v) "Low": This rating indicates either the addition or relocation of components resulting in a slight increase in volumetric requirements.

Table 4-2

Key to Guideline Evaluation Code

A. Sensitivity to Down Time (s): "High" (3_s), "Medium" (2_s), "Low" (1_s)

B. Trade-off Factors:+

1. Volume increase (v): "High" (3_v); "Medium" (2_v), "Low" (1_v)
2. Cost increase (c): "High" (3_c), "Medium" (2_c), "Low" (1_c)
3. Failure rate increase (f): "High" (3_f); "Medium" (2_f), "Low" (1_f)

Examples of good or "easy decision" rating situations:

* Test points are provided for testing essential waveforms and when terminals are not readily accessible. (3_s--1_v, 1_c, 1_f)

* Test point should not be obstructed by cables, components, etc. (2_s--1_v, 1_c)

* Test points should be clearly identified for easy location in the assembly by a contrasting color. (1_s--1_c)

Examples of problematical or "difficult decision" rating situations:

* To the greatest extent possible, assemblies, subassemblies, and modules should be standardized and interchangeable within and between equipments. (3_s--2_v, 1_c, 2_f)

* Replaceable modules are used whenever possible in equipment design. (3_s--3_v, 3_c, 1_f)

* Equipment is modularized such that weight of removable components is below 20 pounds whenever possible. (3_s--2_v, 2_c, 2_f)

+The maintainability design factors which will be easiest to implement have no trade-off rating or a "Low" trade-off or penalty rating in terms of volume (1_v) cost (1_c), and failure rate (1_f). Where no trade-off rating is shown, the reader should interpret this as a negligible or, in some cases, even a positive effect (reduction in volume, cost, or failure rate) on the equipment design.

Note: The effect of some guidelines on equipment space or volumetric measurements may be either negligible or beneficial (i.e., result in a reduction of volumetric requirements). Therefore, there is no equipment space or volume penalty. In such cases, the volume factor (v) in the total evaluation has been eliminated

2) Cost (c): The extent to which total equipment cost is increased by each design factor. This includes the cost of additional components, time required to meet special design and fabrication requirements (usually translatable into dollars), and the cost of additions to the equipment maintenance manual.

(3_c) "High": This rating indicates that the design factor will most likely result in the addition of expensive components, long lead times, or a large design and fabrication cost.

(2_c) "Medium": This rating indicates that the design factor will probably result in a moderate increase in costs and/or design and fabrication time.

(1_c) "Low": This rating indicates that the design factor will probably result in the addition of inexpensive components or a minor modification of the unit.

Note: The effect of some guidelines on cost may be either negligible or beneficial (i.e., result in a savings). Therefore, there is no cost penalty. In such cases, the cost factor (c) in the total evaluation has been eliminated.

3) Failure Rate (f): The extent to which the equipment failure rate is increased by each maintainability design factor.. This may include the effects of: (1) added circuit components and wiring; (2) changes in temperature or rating factors of components; and/or (3) reduced resistance to environmental stress.

(3_f) "High": This rating indicates that incorporation of the maintainability design factor will most likely cause a large increase in equipment failure rate due to the addition of critical components,and/or reduced resistance to environmental stress

(2_f) "Medium": This rating indicates that a moderate increase in failure rate will probably result due to additional wiring, non-critical components, or reduced resistance to environmental stress.

(1_f) "Low": This rating indicates that incorporation of the design factor will probably have a slight effect on failure rate.

Note: The effect of some guidelines on equipment failure rate may be either negligible or beneficial (i.e., result in a reduction of the failure rate). Therefore, there is no penalty in terms of failure rate. In such cases, the failure rate factor (f) in the total evaluation has been eliminated.

3. Maintenance Manuals and Troubleshooting Procedures

* The correct magnitudes and waveshapes should be shown for all equipment outputs. (3_s--1_c)

* Electrical schematics and wiring diagrams for all circuits should be included. (Schematics show the flow of signals through the system and wiring diagrams show the point-to-point connections.) Voltage or current magnitudes and waveshapes should be shown at all critical test points. (3_s--1_c)

* The maintenance procedure should be described clearly and concisely so as to minimize and simplify the decisions required by the technicians. Included in this description are the procedures required to gain access to and troubleshoot the equipment. Instructions are also provided on the replacement of components, alignment and adjustment, and checkout of the unit. (3_s--1_c)

* The maintenance procedure should allow troubleshooting to be carried out in the following three phases:

  a) A routine check of the system to identify or verify malfunction symptoms.

  b) The use of troubleshooting charts to determine which components or assemblies can cause the malfunction being investigated.

  c) Special checks to isolate the malfunction to a replaceable or repairable unit. (3_s--1_c)

* Exploded views should be included for all repairable unit assemblies and subassemblies. Instructions are furnished for the disassembly and replacement of these units. (3_S--1_C)

* A troubleshooting guide should be included in the maintenance manual. This guide usually lists the malfunction symptoms, the action(s) to take for each symptom or group of symptoms, and the alternatives to each action depending on its outcome. (Actions should terminate at the replaceable or repairable unit.) The recommended format for the troubleshooting guide is shown in Figure 4-9. (3_S--1_C)

* This troubleshooting guide should specify the action alternatives at each step to the extent required by the following factors:

  a) Skill level of the technician, including the decisions he is capable of making.

  b) Echelon of maintenance.

  c) Maintenance philosophy for the subsystem. (3_S--1_C)

* The guide should also include a troubleshooting technique that is based on:

  a) The probability that a particular component or assembly is the cause of the failure (component or assembly failure rate experience).

  b) The time, skill, and effort required to perform each check and its relative information value in isolating a failure.

  c) The test equipment type required for each check.

  d) The engineering design and configuration of the equipment. (3_S--1_C)

* For any extended troubleshooting procedure the technician should also be referred to an appropriate signal flow diagram as an aid in analyzing malfunction symptom patterns. These diagrams show the signal flow among the possible malfunctioning components or modules for a given symptom pattern. (3_S--1_C)

SYMPTOM PATTERN	TROUBLESHOOTING PROCEDURE
PWR ON indicator lights are out.	1. Check PWR ON circuit breakers. 2. Check fuses F501, F502 and F515 and replace if defective. 3. Check ship's power available.
LOP and LPP indicator lights for one tube are out; PWR ON lights are on	1. Check fuses F504 and F505; replace if defective.
Half or all of LOP indicator lights fail to come on during lamp test	1. See (appropriate signal flow diagram).
HOLDDOWNS ENGAGED indicator light on LPP fails to come on when HOLDDOWNS switch is at ENGAGE during loading	1. If L119 is energized, but clamps are not engaged, refer to (appropriate BuShips manual or signal flow diagram). 2. See (appropriate signal flow diagram) for checkout of hydraulic supply.
MOUNT DOORS LOCKED SHUT indicator light on LPP fails to go out when MOUNT TUBE DOORS switch is placed at UNLOCKED	1. See (appropriate signal flow diagram) for checkout of solenoids.

Figure 4-9. Recommended format for a troubleshooting guide. (Adapted from Missile launching system Mark 15 Mod 0, OP 2726, p. 5-13ff.)

An example of the recommended general format for a signal flow diagram is shown in Figure 4-10.

* The signal flow diagram should:

a) Emphasize the nature of the signal flow between components or modules, particularly at point where "Power On" checks can be made.

b) Deal only with the electrical characteristics of the signal, not with the electrical characteristics of components.

c) Show the signal characteristics to be checked at each test point. Complex time and shape characteristics of a signal can be keyed to tables at the edge of the diagram or on separate pages.

d) Provide information about the nature of signal flow down to, but not within, units which are replaceable (or throw-away) at the level of maintenance for which the diagram is prepared.

e) Base diagrams on a particular configuration of control settings for the prime equipment and/or test equipment and on given conditions for feedback loops, servos, etc. Indicate the control settings and special conditions on the diagram.

f) Identify components by reference designations.

g) Make the appearance of signal flow diagrams similar whether they deal with signal flow from among major units, assemblies, or subassemblies. (3_S--1_C)

The sequence-of-checks diagram is used in conjunction with a signal flow diagram. It gives the best sequence of checks to be used for a particular malfunction symptom pattern. It directs the technician's attention to the next test point which varies depending on whether the last reading was in or out of tolerance. The family tree method for presenting sequence of checks diagrams is presented in Figure 4-11. If space permits, the sequence-of-checks diagrams should appear on the same or facing page with its related signal flow diagram.

* These sequence-of-checks diagrams should:

a) Specify the sequence of checks that first isolates the malfunction to a single series chain.

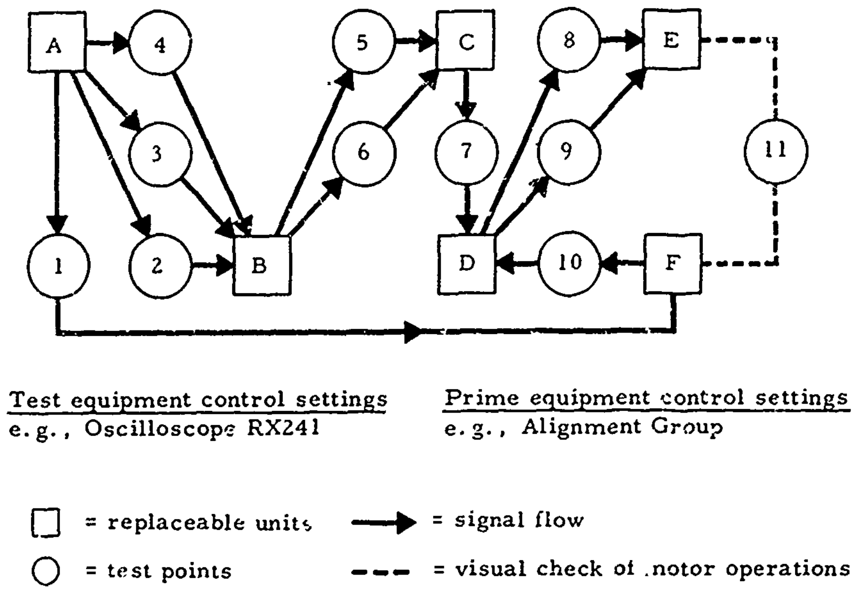


Fig. 4-10. Recommended generalized format for a signal flow diagram.[9] (Voltages, resistances, and waveforms appear on the diagram or in a table underneath.)

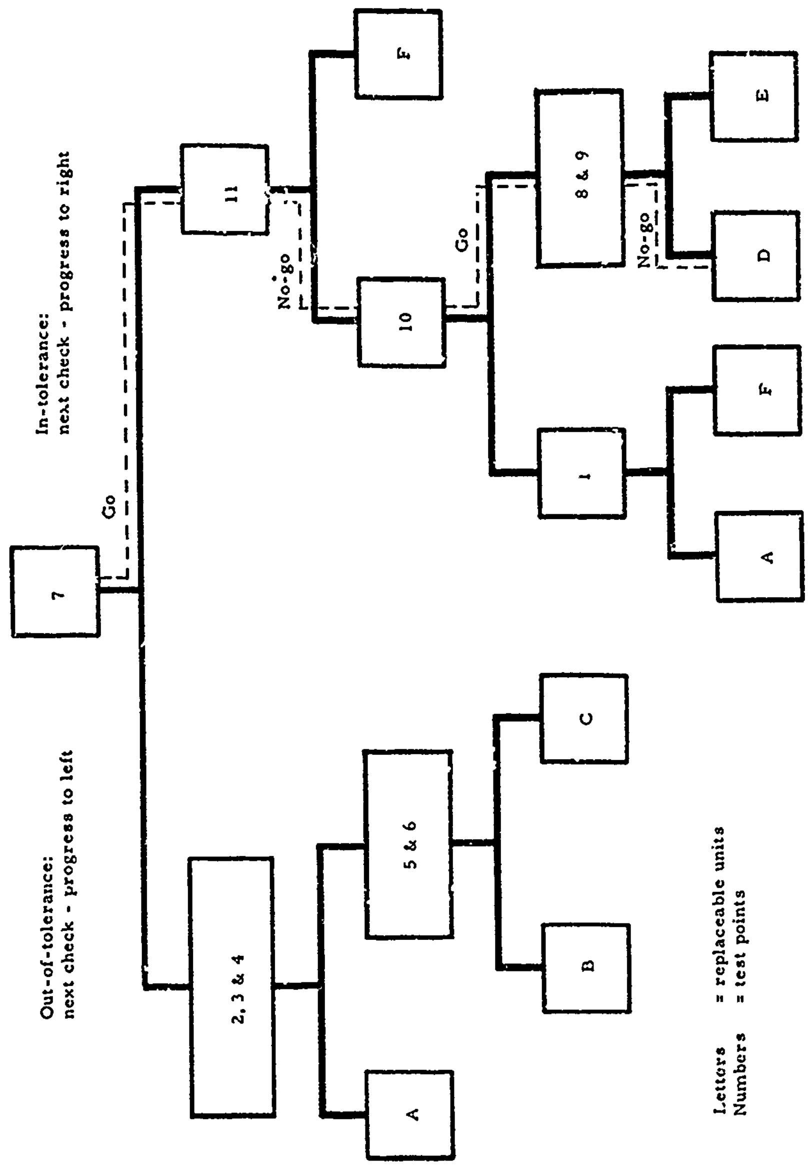


Fig. 4-11. Sequence-of-checks diagram: Tree method.
(Sequence is keyed to signal flow diagram in Fig. 4-10.)

b) Specify a sequence of checks within the chain that is most efficient depending upon such factors as the probability that a component is the cause of the malfunction, time to perform each check, and the specific design of the equipment. (3_s--1_c)

* The translation of schematic information into its physical counterpart should be simplified, particularly where complex electronic circuitry is involved, by one of the following means:

a) A symbolic coding system (e.g., see coding of test points on page 272) using symbolic numbers, color, etc.

b) A pictorial representation of the chassis (e.g., the "photofacts" technique used in commercial radio and television repair) with identification of salient points and maintenance instructions included in the reproduction. (3_s--1_c)

4. Failure Indication

* An indicator light should be provided to reveal when a power failure occurs. (3_s--1_v, 1_c, 1_f)

* Indicator lights with dual lamps for each function (energized simultaneously) are preferred, since positive indication of operation is provided even if one lamp fails. However, indicator lights using a single lamp may be used if failure of the equipment is obvious and a lamp test feature is provided. (3_s--1_v, 1_c, 1_f)

* One or more displays should be provided to indicate when equipment outputs are not within tolerance limits.. (If not, see Test Equipment.) (3_s--2_v, 2_c, 1_f)

* An auditory alarm is provided to indicate an equipment malfunction if the equipment is not regularly monitored. (3_s--1_v, 2_c, 1_f)

5. Test Equipment

* Built-in test equipment and selector switches are provided to monitor outputs periodically if it is not possible to furnish a separate display for each output. (3_s--3_v, 3_c, 2_f)

* If built-in test equipment is not provided, it should be possible to check and adjust a unit using easily portable test equipment. (3_s--1_v, 2_c, 2_f)

* Test leads and adaptors should be stored in the lid or cover of the test equipment. (1_s)

* Adequate space should be available for test equipment placement. If possible, console units are equipped with trays on which test equipment can be mounted. (2_s--2_v, 1_c)

* If possible, drawer space should be provided in units so that spare test cables, adaptors, and tools can be stored. (1_s--3_v, 2_c)

5.1 Types of Test Equipments+

Common test equipments can be placed into one of the three following categories:

a. General Purpose Test Equipment

This category includes individually packaged portable commercial or military laboratory-type test equipments which can be used to check and test one or more equipment parameters. Examples of such equipment include oscilloscopes, VTVMs, VOMs, and tube testers.

b. Built-in Monitoring Equipment

Equipment in this category is an integral part of the prime equipment. Such built-in equipment (varying in complexity) can be used for automatic monitoring and failure detection during the course of equipment operation.

+See Table 4-3 for factors in test equipment selection.

c. Special Purpose Automatic or Semiautomatic Check-out Equipment

These equipments may be truly automatic or semi-automatic, designed for checkout of a specific system or subsystem, and used to check functioning prior to a mission or similar period of use.

6. Test Points

* When external test equipment is required to check a unit, appropriate test points are located on the outer case of the unit. (Fig. 4-12) (3_s--1_v, 1_c)

* It should be possible to check the unit in its operating condition without the use of special rigs and harnesses. (2_s--1_v, 1_c, 2_f)

* If it is necessary to furnish signal inputs to the unit under test, a test connector should be available on the unit. The connector is located on the front panel of the unit when the test equipment is used in conjunction with the other displays on the front panel. (2_s--1_v, 1_c, 2_f)

* Test points are provided for testing essential waveforms and when terminals are not readily accessible. (3_s--1_v, 1_c. 1_f)

* When feasible, test points should be grouped in a line or matrix to reflect the sequence of tests to be made. (Fig. 4-13) (2_s)

* Test points used for component adjustment should be located close to the controls and displays also used in adjustment. (2_s--1_v)

* Test points should not be obstructed by cables, components, etc. (2_s--1_v, 1_c)

* Test points should be appropriately labeled by symbol or name. (2_s--1_v, 1_c)

* Test points should be clearly identified for easy location in the assembly by a contrasting color. (1_s--1_c)

* Job instructions coded to test points are provided when it is not feasible to provide full or detailed information at the test points. (3_s--1_c)

* Desired signal and tolerance limits of test points are specified, preferably at the test points themselves. (3_s--1_v, 1_c)

Table 4-3

Factors in Test Equipment Selection
(the comments in the boxes are ratings)

Factor	Element	Built-in	Special Purpose (Automatic or semiautomatic)	General Purpose
Maintenance Technician				
	Personnel Convenience	High	Medium	Low
	Personnel Safety	High	High-Med	Med-Low
	Complexity of Test Equipment Operation	Low	Medium	High
	Time to Complete Tests	Least	Medium	Most
	Personnel Training Time	Least	Medium	Most
	Tendency to Over-depend on Test Equipment	High	High	Low
Physical Factors				
	Limits on Size of Test Equipment	Minimum Limits - Depends on Prime Equipment and Application		Maximum Limits - Limited by Portability
	Limits on Weight of Test Equipment	Minimum Limits - Depends on Prime Equipment Application		Maximum Limits - Limited by Portability
	Complexity of "Wiring in" Test Equipment	High	High	Low
	Need for Additional Test Points in Prime Equipment	None	None	Many
	Space Required in Work Area	Least	Some	Most
	Storage Problems	None	None	Many
	Need for Traffic Considerations	Low	Medium	High

Table 4 (Cont'd)

Factor	Element	Built-in	Special Purpose (Automatic or semiautomatic)	General Purpose
Maintain-ability and Reliability	Probability of Test Equipment Damage	Low	Low	High
	Probability of Damage to Prime Equipment Caused by Testing	Low	Low	High
	Effect on Prime Equipment Operation When Repairing Test Equipment Failures	Some	Slight	None
Logistics	Cost to Incorporate Test Equipment	High	Med-High	None
	Test Equipment Procurement Time	High	Medium	Low
	Design Engineering Effort	High-Med	High-Med	Low
	Compliance of Test Equipment to Same Specifications as Prime Equipment	Must	May	May
Application	Advantage of Long Duration and High Frequency Usage in Given Location	High	High-Med	Low
	Versatility of Application	Low	Low	High
	Opportunity for Incorrect Usage	Low	Low	High
	System Adaptability to New Test Equipment	Low	Medium	High

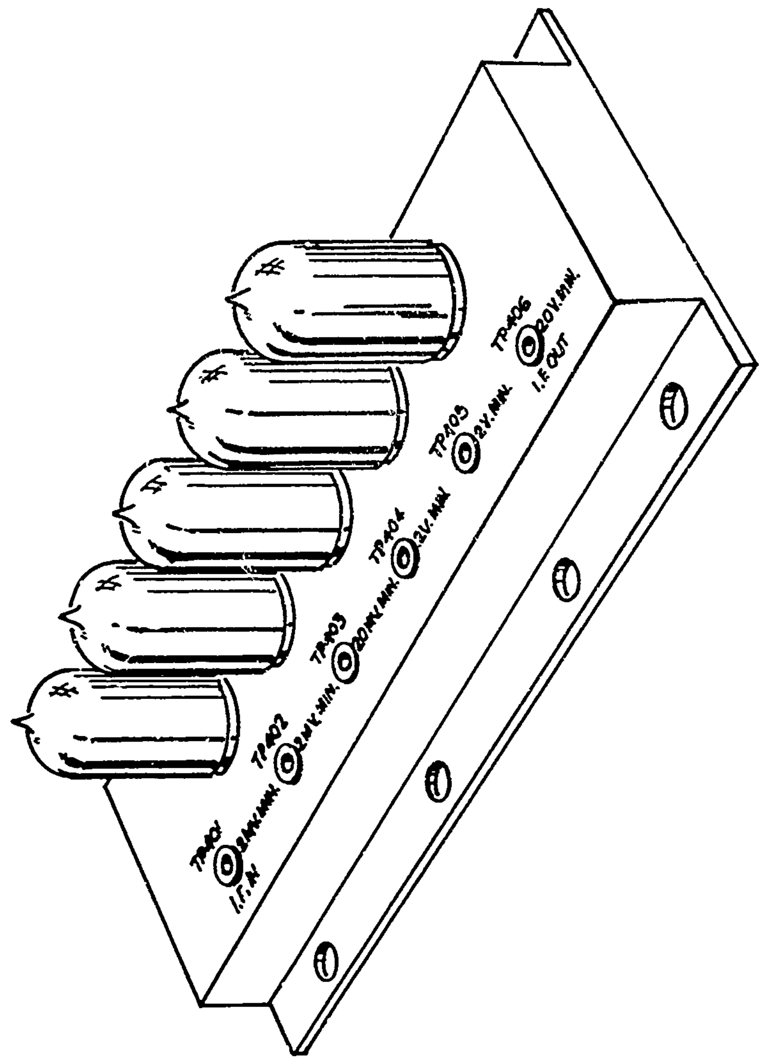
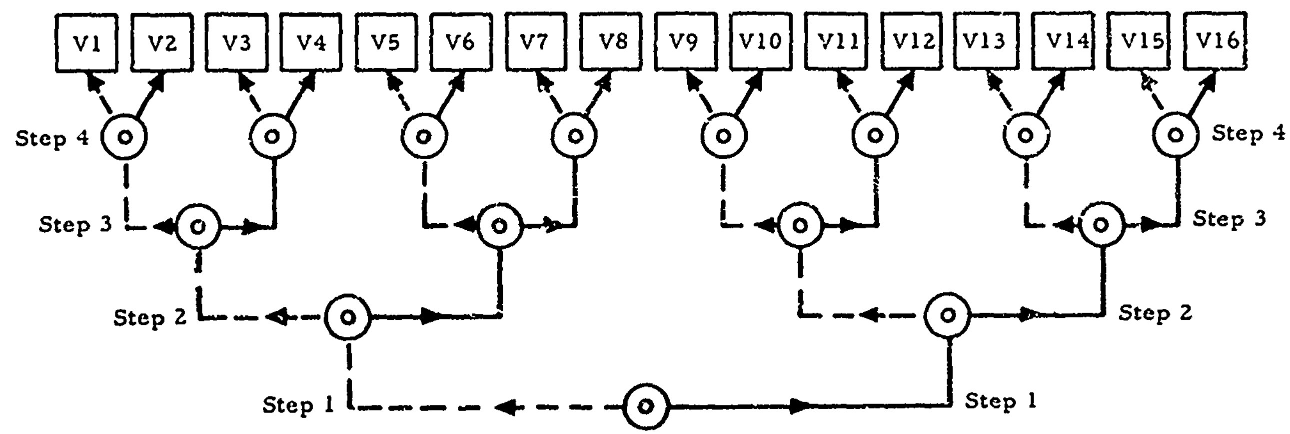


Fig. 4-12. Identification of test points. (24)



NOTE: Technician starts at Step 1 test point and follows solid line, if a proper signal is present, or the broken line if it is not present. This procedure is followed until the malfunction is isolated to the lowest functional level.

Fig. 4-13. Grouping of test points for half-split method.(24)

* Contact points of test points should have sufficient strength to prevent their bending. $(2_s - - 1_c)$

* When feasible and not in conflict with other requirements, a test point is supplied at the input and output of each throwaway component. $(2_s - \cdot 1_v, 1_c)$

6.1 Functional Test Point Coding+

6.1.1 General

Functional test point coding uses symbolic and notational identifications applied to the basic types of measurement points within the circuit considered. The symbols and notations make possible a systematized identification method which presents a maximum of information on schematics, in technical manuals, and on the equipment itself.

Although test point coding is intended generally for use on two- or three-stage sections of interdependent circuits, it may be used throughout the equipment. The method employs:

a. Dynamic basic circuit test points++ which are inputs or outputs. The symbol for these test points is a star.

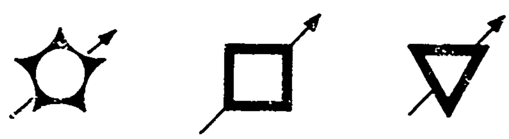
+After Maintainability design criteria (24).

++A dynamic test point is one used for taking measurements with a signal, either inherent or injected, in the circuitry. (A static test point is one used for taking measurements with the absence of any signal or used in such a way that the presence of a signal in the circuit has negligible effect on the readings being taken.)

b. Identification of dynamic intracircuit test points which essentially denote the performance of intervening circuits or related circuitry. This measurement affects maximum diagnostic efficiency of intracircuit analysis after the dynamic basic circuit measurements are completed and is a key measurement. The use of this measurement generally eliminates further or nonessential testing. The symbol for these test points is a square.

c. Penetration into intracircuit analysis through a series of dynamic subcircuit test points. The symbol for these test points is a triangle.

d. Indication that the parameter being measured is dependent on variations in normally related circuit controls (e.g., by placement of a diagonal arrow through the symbol).



e. A consideration of the type of functional measurement to be made and the test equipment to be used (e.g., by placing the letters AC (for AC Voltmeter), DC (for DC Voltmeter), or OS (for Oscilloscope) adjacent to the symbol).

f. The identification and/or illustration of the signal characteristics being measured (when there is sufficient space on the equipment).

The use of these symbols is illustrated in Fig. 4-14, which is a drawing of the NBS Preferred Circuit Number 25--Video Amplifier Chain.

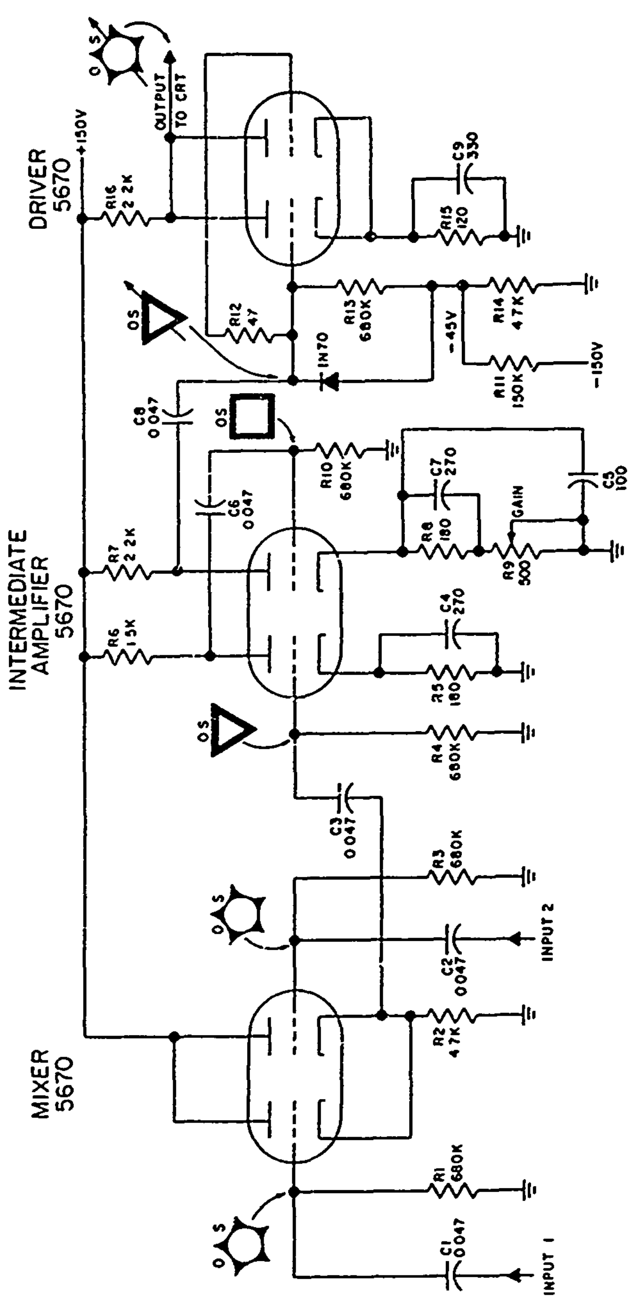


Fig. 4-14. Circuit locations of functional test points. (24)

6.1.2 Advantages of Functional Test Point Coding

The advantage of functional test point coding is in the significant reduction in the time required to troubleshoot. This advantage is realized because the use of the recommended symbols on the equipment will provide the technician with the following information without need for reference to a technical manual:

a. The sequence of importance of test points.
b. The type of test equipment to use.
c. The dependency of a signal on a related variable control.

In the case of catastrophic failures, the technician with limited experience on a specific equipment can perform the complete diagnostic task with only a block diagram. With increased familiarity with the equipment, reliance on the block diagram can be significantly reduced or completely eliminated.

7. Tools

* Variety of tools is held to a minimum. (3_s--1_c)

* As few special tools as possible are required. (3_s--1_c)

* Tools and test leads to be used near high voltage should be adequately insulated. (2_s--1_c)

* Metal handles should be avoided on tools likely to be used in extreme cold or heat. (1_s--1_c)

* Speed and ratchet-type and/or offset tools are provided when necessary. (2_s--1_c)

8. Weight

* Equipment is modulari… such that weight of removable components is below 20 pounds whe… er possible. (3_s--2_v, 2_c, 2_f)

* Materials or components to be carried short distances by one man do not exceed the following values:

Maximum allowable weight (lbs.)	Height lifted from ground (ft.)
142	1
139	2
77	3
55	4
36	5
20	6

(3_s--2_v, 2_c, 2_f)

9. Handles

* When possible, handles should be provided on covers, drawers, and components to facilitate handling. (1_s--1_v, 1_c)

* Recessed rather than extended handle fixtures should be provided to conserve storage space and to preclude injury by accidental striking of the handles. (1_s--1_v, 1_c)

* When handles cannot be provided, hoist and lift points should be clearly marked. (1_s--1_c)

* When possible, handles are located over the center of gravity to prevent the object from tipping while being lifted or carried. (2_s)

* Handles should be positioned so that they cannot catch on other units, wiring, protrusions, or structural members. (1_s)

* Handles should be placed on any component which might be difficult to grasp, remove, or carry or wherever there is a tendency to use fragile components as handholds. (1_s--1_c)

* The following dimensions are minimum for handles to be used by the ungloved hand: (Fig. 4-15)

a. Weight to be lifted or moved is under 25 pounds:

Handle diameter (A): 1/2 inch
Finger clearance (B): 2 inches
Handle width (C): 4-1/2 inches

b. Weight to be lifted or moved is over 25 pounds:

Handle diameter (A): 3/4 inch
Finger clearance (B): 2 inches
Handle width (C): 4-1/2 inches (2_s)

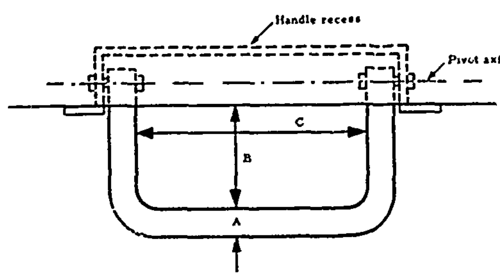


Fig. 4-15. Recommended dimensions for recessed handles.

10. Covers, Cases, and Access Doors

* Method of opening a cover is evident from the construction of the cover itself. If not, instructions are permanently attached to the outside of the cover. (2_s--1_c)

* Covers, cases, and access doors should be designed to minimize the number of fasteners required. (2_s)

* Structural members, other components, etc., should not interfere with opening or removal of a cover. (2_s--2_v, 1_c)

* Provision for adequate bonding of plastic or rubber stripping and seals should be made so that if a cover comes into contact with or must slide over such material the seal will not be damaged or the cover jammed. (2_S)

* When the cover is in place, the fact that it is secured (or not secured) should be evident. (1_S)

* Ventilation design should prohibit insertion of test probes, screwdrivers, or other tools. (1_S)

* Assemblies are designed so that wires and other components will not be damaged when the cases are put on or taken off. (2_S)

* Where possible, cases are designed to lift off the components rather than the components designed to lift out of the cases. (2_S)

* Where feasible, guides, tracks, and stops are provided to facilitate handling and to prevent damage to components. (2_S--1_V, 1_C)

* When access doors must be hinged at the top, a safe and convenient method should be provided to hold the cover open. (2_S--1_C)

* Hinged doors or covers should be provided with minimum number of captive quick-opening fasteners to meet requirements. (2_S)

* If instructions applying to a covered unit are lettered on a hinged door, the lettering should be properly oriented for reading when the door is open. (1_S)

* When possible, the same size and type of fasteners are used for all covers, cases, and access doors. (2_S)

* Maximum use should be made of tongue-and-slot catches (e.g., "Dzus" type) to minimize the number of fasteners required. Hand-operated fasteners which require no tools are preferred. (Figs. 4-16, 4-17) (2_S)

* Where compatible with stress and load considerations, fasteners for mounting components and equipment require at most one complete turn. (2_S)

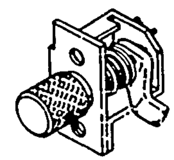
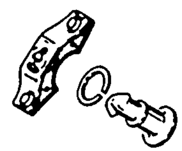
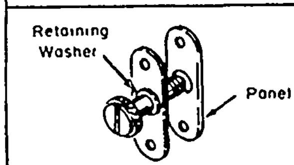
Type	Description	Maintainability Considerations	Approximate Operating Time
	Adjustable pawl fastener As knob is tightened the pawl moves along its shaft to pull back against the frame. 90° rotation locks, unlocks fastener.	1. No tools required.	0.1 min.
	"Dzus" type fastener with screw-driver slot Three-piece 1/4 turn fastener. Spring protects against vibration. 90° rotation locks, unlocks fastener.	1. Tools may be required. 2. Should not be used for front panel fasteners or in structural applications. Preferred type for light weight panels other than front panels.	.05 min.
	Wing head. "Dzus" type 90° rotation locks, unlocks fastener.	1. No tools required. 2. Should not be used for front panel fasteners or in structural applications. Preferred type for light weight panels other than front panels.	.04 min
	Captive fastener with knurled, slotted head The threaded screw is made captive by a retaining washer.	1. Tools may be required. 2. Operating time depends on number of turns required.	0.4 min.

Fig. 4-16. Types of fasteners.(24)

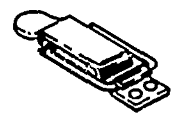
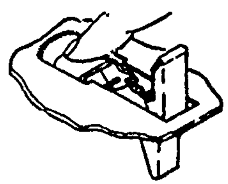
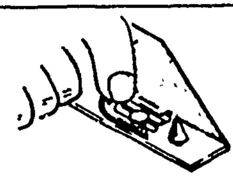
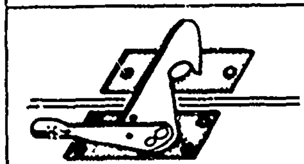
Type	Description	Maintainability Considerations	Approximate Operating Time
	Draw hook latch Two-piece, spring latch, base unit and striker. Engagement loop is hooked over striker and lever is depressed, closing unit against force of springs. Lever is raised to unhook.	1. Relatively slow action. 2. Requires considerable force to disengage loops.	.03 min.
	Trigger action latch One-piece, bolt latch. Latch is opened by depressing a trigger to release bolt which swings 90° under spring action. To close move bolt back into position.	1. Extremely fast action type latch. 2. Strong spring action might cause personal injury.	.01 min.
	Snapslide latch One piece snapslide. Latch is opened by pulling lever back with finger to engage release lever.	1. Fast action.	.02 min.
	Hook latch Hook engages knob on striker plate. Handle is pulled up locking in place. To release reverse procedure.	1. Relatively slow action. 2. Takes up room on equipment.	.03 min.

Fig. 4-17. Types of latches. (24)

* If bolts are required, a minimum number of turns are required to tighten or loosen them. (2_s)

* Where heavy bolts are required for access covers, they should be captive. (2_s--1_c)

* Bolts requiring high torque should be provided with hexagonal heads. (2_s)

* To prevent stripping of threads, screws of different threads should be of different diameters. (2_s)

11. Accessibility

* Information placed at each access includes the following:

  a. Nomenclature of items accessible through it.
  b. Names of auxiliary equipment to be used at it.
  c. Periods for accomplishing operations.
  d. Warnings of hazardous or critical operations. (2_s--1_c)

* Edges of accesses should have internal fillets or other protection if they might otherwise cause injury to hands or arms. (2_s--1_c)

* Access provisions should be located on easily accessible surfaces. (2_s)

* Components are not placed in recesses or located behind or under stress members, floor boards, seats, hoses, pipes, or other items which are difficult to remove. (3_s--1_v, 1_c)

* Check and adjustment points, cable end connectors, and labels are accessible and, where possible, face the operator. (2_s--1_v, 1_c)

* Access to functions which the technician must observe are large enough for adequate view. (2_s)

* When visual access only is required, the following practices in order of preference are followed:

  a. Opening with no cover is used unless this is likely to degrade system performance.

b. Plastic window is used if dirt, moisture, or other foreign materials are a problem.

c. Break-resistant glass window is used if physical wear or contact with solvent will cause optical deterioration.

d. Quick-opening metal cover is used if glass does not meet stress or other requirements. (3_s)

* When access for tools, test leads, and service equipment is required, the following practices, in order of preference, are followed:

a. Opening with no cover is used unless this is likely to degrade system performance.

b. Sliding or hinged cap is used if dirt, moisture, or other foreign materials are a problem.

c. Quick-opening cover plate is used if a cap will not meet stress requirements. (3_s)

12. Openings[+]

* Smallest allowable openings for one-hand tasks are as follows:

a. Inserting empty hand held flat: 2-1/2 by 4-1/2 in.

b. Smallest square hole through which empty hand can be inserted: 3-1/2 by 3-1/2 in.

c. Inserting miniature vacuum tube, held with the thumb and first two fingers, up to the center knuckle of the middle finger: 2 by 2 in.

d. Inserting large vacuum tube, held with the thumb and first two fingers, up to the center knuckle of the middle finger: 4 by 4 in.

e. Using 8-inch screwdriver with a 1-inch diameter handle: 4 by 4 in.

[+]See Figures 4-18 and 4-19.

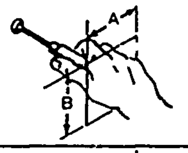
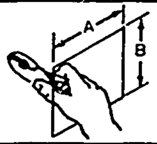
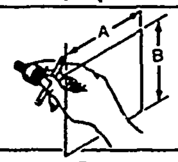
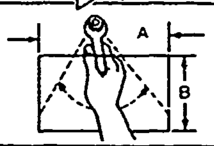
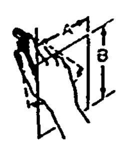
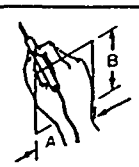
Opening Dimensions	Dimensions+ (In Inches) A	B	Maintenance Task
	4.2	4.6	Using common screwdriver, with freedom to turn hand through 180°.
	5.2	4.5	Using pliers and similar tools.
	5.3	6.1	Using "T" handle wrench, with freedom to turn hand through 180°.
	10.6	8.0	Using open-end wrench, freedom to turn wrench through 60°.
	4.8	6.1	Using "Allen" type wrench, freedom to turn wrench through 60°.
	3.5	3.5	Using test probe, etc.

Fig. 4-18. Recommended openings for using common hand tools.

+The dimensions are extrapolated from data presented in "Guide to Design of Electronic Equipment for Maintainability." WADC Technical Report 56-218, Wright Air Development Center, Wright-Patterson Air Force Base. Ohio, 1956; and "Anthropometry of One-Handed Maintenance Actions," Technical Report NAVTRADEVCEN 330-1-3, U.S. Naval Training Device Center, Port Washington, New York, 1960.

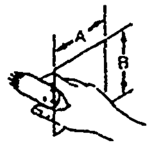
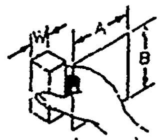
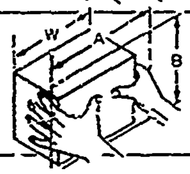
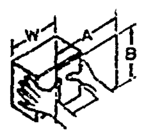
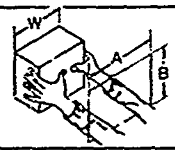
Opening Dimensions	Dimensions+ (In Inches) A	B	Maintenance Task
	4.2	4.7	Grasping small objects (up to 2-1/16" diameter).
	W+1.75	5.0++	Grasping large objects with one hand (2-1/16" wide).
	W+3.0	5.0++	Grasping large objects with two hands, with hands extended through openings up to fingers.
	W+6.0	5.0++	Grasping large objects with two hands, with hands extended through openings up to wrists.
	W+6.0	5.0++	Grasping large objects with two hands, with arms extended through openings up to elbows.

Fig. 4-19. Recommended rectangular openings for grasping parts.

+The dimensions are extrapolated from data presented in: "Guide to Design of Electronic Equipment for Maintainability," WADC Technical Report 56-218, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1956; and "Anthropometry of One-Handed Maintenance Actions," Technical Report NAVTRADEVCEN 330-1-3, U.S. Naval Training Device Center, Port Washington, New York, 1960.

++Or sufficient to clear part if part is larger than 5.0".

f. Inserting and tightening AN plug (14-pin connector, outside diameter of 1-7/8 inch.); 4-1/4 by 4-1/4 in.

g. Inserting small assembly: use maximum cross-sectional dimensions of assembly plus 1-3/4 in. (3_s)

* Smallest allowable openings for two-hand tasks are as follows:

a. Inserting drawer or electronic assembly grasped by handles on front, into opening: 1/2 inch clearance on each side of assembly.

b. Reaching through opening with both hands to depth of 6 to 25 inches: width--3/4 the depth of reach; height--4 inches.

c. Reaching in to full arm length (to shoulders), straight ahead, with both arms: width-- 20 inches; height--4-1/4 inches. (3_s)

13. Modular Design

There is insufficient research in the area of equipment packaging to say that any one packaging technique is best for all cases. However, the findings in the literature generally agree that, where complex electronic equipment is involved, the logical signal flow technique considerably enhances the maintainability of equipment. If a training program is added to explain the method to technicians, the advantage should be even more noticeable. The use of the logical signal flow method can also simplify demands for supporting manuals.

13.1 Packaging Methods

Packaging methods which seem to offer the most promise for reduction in down time include:+

a. Logical signal flow.
b. Complete circuit.
c. Component grouping.
d. Frequency characteristic grouping.

+More detailed accounts of how actual equipment was constructed using these techniques are contained in McKendry, et al., Design for Maintainability, Technical Supplement 1. (21)

A brief discussion of these packaging techniques will serve to define these terms and point out the advantages of each technique.

13.1.1 Logical Signal Flow

This technique employs logical flow packaging. Here two ideas are combined: first, that the use of modules in the subchassis will enhance maintenance; and second, that the concept of "data" or "signal flow" is critical to the maintenance problem. Evidence for such a statement has been supplied by Rulon Schweiker, and Gilbert [34], who utilized the technique in a proposed troubleshooting course.

In the logical signal flow method, interaction effects which complicate troubleshooting are handled by taking feedback loops, which could cause confusion, and separating them from the main trunk line. These are arranged so that each of these separate loops in itself takes on a uni-directional signal flow which can be checked out as the main "signal line."

What goes on inside a module in the logical signal flow method is determined by examining what happens to the basic signal while it is enroute through the system. When a change occurs in the signal which is readily perceivable by a technician checking it, the stage is marked off as a potential module. Modules are combined into subassemblies by the same method. Actually the modules turn out to be similar to those of the circuit method and in many cases the two would be identical. However, the method by which the modules are combined differs greatly for the two methods.

13.1.2 Complete Circuit

In the complete circuit packaging method, all similar or identical circuits are grouped physically, and each circuit is placed in a separate module. The tube associated with this circuit can be placed either on top of or inside the module. Since equipment can be thought of as a series of functioning circuits, it is reasonable to think that troubleshooting would be enhanced by using a circuit-grouping technique.

13.1.3 Component Grouping

The component packaging method involves grouping all components of a similar nature in one place in the equipment; for example, all tubes are together, all transistors, etc. Cheap components, such as resistors and capacitors, are placed on separate plug-in type boards which are mounted

under the chassis. The resistors and capacitors are subdivided on different boards. For resistors there is a ground board, a feedback board, a B+ board, etc. The rationale for such a method is that the components which take much time to replace can be checked by a mass replacement technique that will still keep costs low. In addition, there is a great potential for a simplified checkout procedure when all of the elements are in one place and similar.

13.1.4 Frequency Characteristic Grouping

The last method considered employs a frequency grouping in which elements of a unit which have a particular frequency characteristic are placed in one portion of the equipment. The advantage would stem from the ability to use one given piece of test equipment in one given section of the equipment.

13.2 Recommendations for Modular Design

* Replaceable modules are used wherever possible in equipment design. (3_s--3_v, 3_c, 1_f)

* When practicable, modularize on the basis of logical signal flow and detectable changes in signal flow. (3_s--1_v, 1_c, 1_f)

* The number of inputs to and outputs from each replaceable unit (module) is minimized, i.e., circuits are grouped so that minimum crisscrossing of signals between units is required. (3_s--1_c)

Modules and subassemblies should be chosen so that only a single simple input and output check would be necessary to isolate a trouble to that unit. The actual configuration of the equipment should be meaningful and readily comprehensible. Groupings should be chosen so that a large segment of parts can be easily checked by a simple action of the technician.

* Packaging is designed so that complete circuits (one or more) are contained within a single module. (3_s--1_c)

Modules would be maximally efficient if each performed a specific function so that, when a failure existed, simple symptom-pattern analysis would lead the troubleshooter directly to the trouble. Furthermore, these modules and subassemblies could parallel the stages shown on a block or sequence-of-checks diagram (see 3., Maintenance Manuals and Trouble-shooting Procedures, page 259) thereby diminishing and possibly eliminating

the need for schematics which have proved troublesome to inexperienced men.

* It is possible to check and adjust each module separately and then connect the modules into a total functioning system with little or no additional adjustment required. (3_s--1_c)

14. Standardization

Standardization, by decreasing the spare parts and training requirements, facilitates the maintenance of modularized equipment.

* To the greatest extent possible, assemblies, subassemblies, and modules should be standardized and interchangeable within and between equipments. (3_s--2_v, 1_c, 2_f)

When several modular units having the same circuit function (e. g. , servo-amplifier with gain of 10) are identical, they may be interchanged even though they are in different locations in the system. Also, modular units with similar functional characteristics (e. g. , three different amplifiers with gains of 22, 25, and 28 respectively) may not have to be designed separetely; instead, a single modular unit with a maximum gain of 28 and a gain adjustment control can be designed to perform all three functions.

* Replaceable components such as modules, tubes, etc. , are limited to as few different types as possible. (3_s--2_v, 1_c. 2_f)

* Screws and bolts are limited to an absolute minimum number of types and sizes. (3_s)

15. Controls

(These are internal equipment controls used for alignment and adjustment.)

* Alignment and adjustment controls are neither so fine that a number of turns are required to obtain a peak value nor so coarse that the peak position is quickly passed. (3_s)

* Component selection and circuit design are such that the alignment procedure is a straightforward operation, i. e. , it is not necessary to readjust earlier stages after adjusting a later stage. (3_s)

* Alignment controls are so located that they can be readily operated while observing the display associated with the function being adjusted. (2_s)

* Alignment or adjustment controls which are susceptible to vibration or shock should have a positive locking device to assure retention of settings. (2_s--1_v, 1_c)

* Screwdriver adjustments which must be made blind should have the screws or shafts mounted vertically so that the screwdriver will not fall out of the slot. (2_s--1_c)

* Sensitive adjustments are so located or guarded that they cannot be accidentally disturbed by personnel. (3_s--1_v, 1_c)

16. Mounting and Location of Components

* Only interconnecting wiring and structural members should be permanently attached to the unit frame. Electrical components should be mounted on plug-in subassemblies. (3_s--2_v, 1_c)

* Components should be mounted on one side of a board and wiring (including printed or soldered circuits) on the other, with electrical contacts made through the board. (Fig. 4-20) (2_s--1_v, 1_c, 1_f)

* Whenever possible, components are so located that no other equipment need be removed to gain access to or remove them. (3_s--1_c)

* If it becomes necessary to place one component behind another, the component requiring less frequent access should be in the rear. (1_s)

* Components frequently removed from their normal installed position for checking are mounted on roll-out racks, slides, or hinges. (3_s--1_v, 1_c)

* Limit stops are provided on roll-out racks and drawers; over-ride of these limit stops is easily accomplished. (3_s--1_v, 1_c)

* Field removable components are replaceable with common hand tools. (3_s)

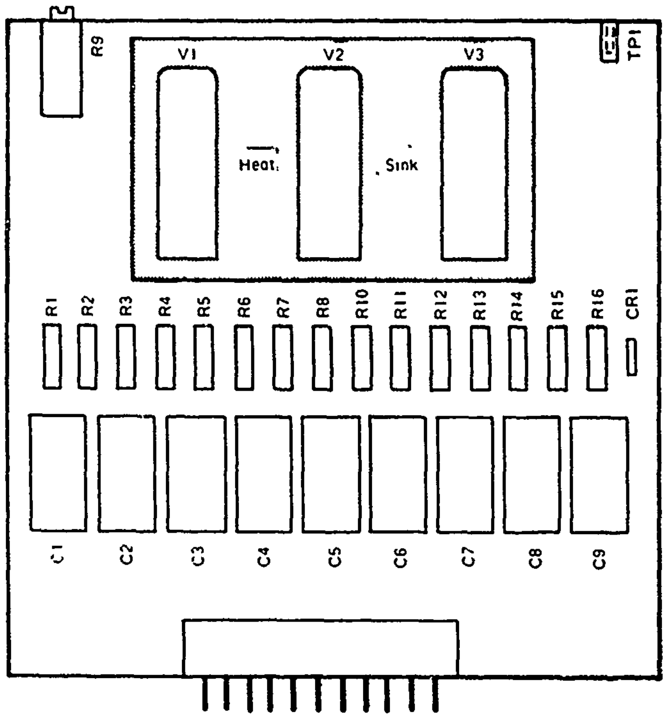


Fig. 4-20. Layout of a typical video amplifier chain on single-sided printed board. (24)

- * Components are not attached to each other; only the component to be replaced has to be removed. $(3_s\text{--}2_v,\ 1_c)$

- * Replaceable components are plug-in rather than solder connected. $(3_s\text{--}2_v,\ 1_c,\ 1_f)$

- * Removal of any replaceable component requires opening or removal of a minimum number of covers or panels (preferably one). $(2_s\text{--}1_c)$

- * Indicator lights are of a type that can be removed from the front of the panel without the use of special tools. The lamp and the filter are not an integral unit. $(3_s\text{--}1_v,\ 1_c)$

- * Guide pins or their equivalent are provided on components for alignment during installation. $(2_s\text{--}1_v,\ 1_c)$

- * Physically similar but electrically non-interchangeable components are so keyed that it is impossible to insert a wrong unit. $(2_s\text{--}1_c)$

- * Components are coded (e. g. , by means of labels) to indicate the correct unit and its orientation for replacement. $(2_s\text{--}1_c)$

- * If mounting screws must pass through covers or shields for attachment to the basic chassis of the component, the screw holes are large enough for passage of a screw without perfect alignment. (3_s)

- * Components are laid out so that a minimum of place-to-place movement by the technician is required during checkout. (2_s)

- * Components should be located and mounted so that access to them may be achieved without danger to personnel (e. g. , from electrical charge, heat, sharp edges and points, moving parts, chemical contamination). $(1_s\text{--}1_v,\ 1_c)$

- * Access to units maintained by one operator does not require removal of equipment by a second, higher-skilled operator. $(3_s\text{--}1_c)$

- * Components such as tube sockets are oriented in a uniform direction to facilitate component replacement. (2_s)

* Large components which are difficult to remove are mounted so that they do not prevent access to other components. $(3_s\text{--}1_c)$

* Components are located so that each replaceable unit can be removed through a single access panel. $(2_s\text{--}1_v,\ 1_c)$

* Components are located where dirt or oil will not drop on them or on the technician performing the maintenance tasks. $(2_s\text{--}1_v,\ 1_c$

* Components are placed to allow sufficient space for use of test equipment and other required tools without difficulty or hazard. $(2_s\text{--}1_v,\ 1_c)$

* All throwaway components are accessible without removal of other components. $(2_s\text{--}2_v,\ 1_c)$

* Structural members of the chassis do not prevent access to components. $(2_s\text{--}2_v,\ 1_c)$

* Delicate components are so located or guarded that they will not be damaged while the unit is being handled or worked on. $(2_s\text{--}1_v,\ 1_c)$

* Components are located so that blind replacement is not necessary. $(2_s\text{--}1_v,\ 1_c)$

* Components of the same or similar form, such as tubes, are mounted with a standard orientation throughout, but are readily identifiable and distinguishable. $(2_s\text{--}1_c)$

The advantages and disadvantages of some of the common component mounting methods are given in Table 4-4.

17. Labeling and Coding

* Each terminal is labeled with the same code symbol as the wire attached to it. $(3_s\text{--}1_c)$

* Labels should be etched or embossed into the component or chassis rather than merely painted or stamped on the surface. $(1_s\text{--}1_c)$

Table 4-4

Part Mounting Considerations for Nonembedded Printed Wiring Board Modular Units(24)

Mounting Method	Advantages	Disadvantages
1. Wired-in tubes and transistors	More reliable connection	Difficult to remove and replace
2. Plug-in tubes and transistors	Easy to remove, test and replace	Electrical connection less reliable
3. Lead-mounted parts	Easy to remove and replace	Large parts will not withstand shock and vibration on lead
4. Clip-mounted parts	Holds part during shock and vibration, easy to remove test and replace	Not necessary for small, light parts
5. Stacking of parts (parts mounted on top of each other)	More parts can be mounted on a unit	Top part has to b removed to reach lower part, making it difficult to test and possible thermal problem
6. Eyelets	Part lead may be soldered and unsoldered many times without damage to eyelet	High resistance may be problem at contact of eyelet and printed wiring unless lead is clinched
7. Plated-through holes	Better connection between plating on hole and printed wiring	Hole may be damaged when removing and replacing parts
8. Terminals	Part lead may be soldered and unsoldered many times without damage to terminal	High resistance may be problem at contact of terminal and printed wiring

* If surface labels must be used, decals or stamped labels are preferable to stenciled labels. $(1_s\text{--}1_c)$

* Labels are not obscured by components. $(2_s\text{--}1_v,\ 1_c)$

* Transformers, chokes, and other potted networks have circuit diagrams with current voltage and impedance ratings stenciled on the outside. $(3_s\text{--}1_c)$

* The coil contacts on relays are clearly marked. $(2_s\text{--}1_c)$

* When feasible, the outside coverings of manufactured electrical components such as capacitors and tubes are stamped with relevant information concerning electrical characteristics of the component. Direct presentation of this information makes interpretation easier than does color coding. $(2_s\text{--}1_c)$

* If feasible, individual conductors of all cables, either single- or multi-conductor, are color coded their entire length. The color coding used throughout a unit is consistent, e. g., +28 VDC is identified by the same color wherever it is used. $(3_s\text{--}1_c)$

* The color coding system used is described in the manual for the unit and, if possible, on printed instructions included within the unit. $(3_s\text{--}1_c)$

18. Cabling and Wiring[+]

* Conductors are bound into cables and secured. $(3_s\text{--}1_c)$

* Cables are long enough so that each functioning component can be checked in a convenient place or, if this is not feasible, extension cables are provided. $(3_s\text{--}1_v,\ 1_c)$

* Cables are long enough to permit jockeying or movement of components when it is difficult to connect or disconnect other cables. $(2_s\text{--}1_v,\ 1_c)$

* If it is necessary to route cables and wires through holes in metal partitions, protection from mechanical damage is provided by grommets or other acceptable means. $(3_s\text{--}1_v,\ 1_c)$

[+] See Table 4-5 for further design considerations.

Table 4-5

Cable and Cable Harness Design Considerations[24]

Type	Design Considerations
Laced Cable Harness	1. Recommended for internal chassis cabling 2. Not recommended for external cabling because protection against moisture and abrasion is insufficient. 3. There is a possibility that the lacing cord will cut the insulation if it is tied too tightly or will slip if it is not tied tightly enough. 4. Relatively easy to repair.
Plastic-Tie Cable Harness	1. Recommended for internal chassis cabling. 2. Not recommended for external cabling because protection against moisture and abrasion is insufficient. 3. Certain types of plastic ties require an installation tool.
Taped Cable Harness	1. Recommended for internal chassis cabling. 2. Not recommended for external cabling because tape tends to separate during . ng, thus exposing wires. 3. Relatively easy to repair, but repair is time-consuming.
Tubular Sleeve Cable Harness	1 Recommended for external cabling. 2. Not recommended for internal chassis cabling because "take-offs" are difficult. 3. Sleeving can withstand extremes in temperature and abrasion. 4. Difficult to repair.
Plastic Spiral Wrapped Cable Harness	1. Recommended for internal chassis cabling. 2. Not recommended for external cabling because spiral tends to separate during flexing, exposing wires. 3. Relatively easy to repair, but time-consuming.
Zipper Sleeve Cable Harness	1. Recommended for external cabling. 2. Not recommended for internal chassis cabling because "take-offs" are difficult. 3. Can be sealed and made moisture-proof. 4 Unsealed zipper sleeve may open when cable is bent sharply. 5. Relatively easy to repair if not sealed.
Jacketed or Molded Cable	1. Recommended for external cabling. 2. Not recommended for internal chassis cabling because "take-offs" are difficult. 3. Usually has high resistance to moisture and abrasion. 4. Usually impossible to repair.
Flat Bonded Cable Harness	1. Recommended for internal cabling, especially where space is at a premium. 2. Not recommended for external cabling because protection against moisture and abrasion is insufficient. 3. Usually impossible to repair.
Printed Wiring Cable Harness	1. Recommended for internal cabling, especially where space is at a premium. 2. Not recommended for external cabling because protection against abrasion is insufficient. 3. Usually lighter than equivalent extruded wire cables. 4. Usually impossible to repair.
High-Frequency Coaxial Cable	1. Used both internally and externally, particularly for high-frequency applications. 2. Usually difficult to repair.
Miscellaneous Cables and Cable Harnesses	1. Usually special-purpose cables and cable harnesses with special characteristics.

* Guards or other safety devices are provided for easily damaged conductors such as wave guides or high-frequency cables. $(3_S\text{--}1_V, 1_C)$

* Electrical cables are not routed below fluid lines. $(3_S\text{--}1_V, 1_C)$

* Cables cannot be pinched by doors, lids, etc. $(2_S\text{--}1_V, 1_C)$

* Cables are routed so they cannot be walked on or used for hand holds. $(2_S\text{--}1_V, 1_C)$

* Cables are easily accessible for inspection and repair. (Table 4-5) $(3_S\text{--}1_V, 1_C)$

* Cables are so routed that they need not be bent or twisted sharply or repeatedly. $(2_S\text{--}1_V, 1_C)$

* If cables terminate on control-display panels, the receptacles are located so that their associated cables do not interfere with controls and displays. $(1_S\text{--}1_V, 1_C)$

* If other test points are not available, fan-out cables in junction boxes should be provided as check points. This requires that each check point be accessible for test probes and clearly labeled. $(3_S\text{--}2_V, 1_C)$

* Lugs used for connection to screw terminals should permit rapid removal (such as fork instead of ring type). (3_S)

* About 1/16-in. pigtail is left on leads soldered to terminals in order to simplify removal. No more than three wires are mounted on one terminal. $(3_S\text{--}1_C)$

* Terminals are separated so that the soldering of a wire to a particular terminal does not damage leads on adjacent terminals. $(3_S\text{--}1_V, 1_C)$

19. Lubrication

* Equipment containing mechanical components either has provision for lubrication without disassembly or does not require lubrication. $(3_S\text{--}1_V, 2_C)$

* When lubrication is required, the type of lubricant to be used and the frequency of lubrication is specified by a label at or near the lubrication point. (3_s--1_c)

20. Connectors

* Adequate spare connector contacts should be provided. (3_s--1_v, 1_c)

* One-turn or other quick-disconnect plugs are used. (3_s--1_v, 1_c)

* When dirt and moisture are a problem, plugs have attached covers. (1_s--1_v, 1_c)

* Connectors are located far enough apart so that they can be grasped firmly for connection and disconnection. (3_s--1_v, 1_c)

* Plugs are designed so that it is impossible to insert the wrong plug in a receptacle. (2_s--1_c)

* The electrically live or "hot" contacts of a connector are female (socket) type, not male (pin) type. (2_s)

* Connectors and their associated labels are positioned for full view by maintenance personnel. (2_s--1_v, 1_c)

* Mating plugs and receptacles are identified by color or shape or other acceptable means. (2_s--1_c)

* Connectors have painted stripes, arrows, or other indications for proper insertion of aligning pins. (2_s--1_c)

21. Fuses and Circuit Breakers

* Fuses and circuit breakers are so located that they can be easily seen and quickly replaced or reactivated. (3_s--1_v)

* Fuse replacement is not hampered by other components. (3_s--1_v)

* No special tools are required for fuse replacement. (3_s)

* A panel label is provided to indicate signal source and fuse rating. (3_s--1_v, 1_c)

2. Safety (Human Safety)

Safety provisions reduce the accident hazard to the technician. As a result, he is required to take fewer precautions, and troubleshooting time is reduced.

* Provisions are made to prevent personnel from coming into contact with voltages in excess of 70 volts while installing, operating, or interchanging assemblies or plug-in parts. (Table 4-6) (2_s--1_v, 1_c)

* Interlocks are provided where potentials exceed 70 volts. (2_s--1_v, 1_c, 1_f)

* Means are provided for by-passing interlocks for servicing. Warning indicators are included. (2_s--1_v, 1_c, 1_f)

* All external metal parts are at ground potential. (2_s)

* Guards or covers and warning plates are provided for potentials in excess of 350 volts rms on contacts, terminals, and like devices. (2_s--1_v, 1_c)

* All control shafts and bushings are at ground potential. (2_s)

* Protection is provided from imploding cathode ray tubes. (2_s--1_v, 1_c)

* Protection should be provided from moving mechanical parts. (1_s--1_v, 1_c)

* Doors and hinged covers are rounded at the corners and provided with stops to hold them open. (2_s--1_v, 1_c)

* The equipment frame and other large, exposed, noncurrent-carrying parts should be covered with a paint possessing good insulating properties to prevent these parts from becoming potential electrodes. (1_s--1_c)

* Terminals should be rounded rather than sharp to reduce the hazard of electrical shock. (1_s)

Table 4-6

Hazard Classification of Voltages to Ground
According to Component Contact Area for Service-Personnel Exposure[35]

Shock Hazard Class	Voltages (V) and "Hot" Contact Area (A) in sq cm[+]						
	$A \le 0.5$	$0.5 < A \le 1$	$1 < A \le 2$	$2 < A \le 3$	$3 < A \le 4$	$4 < A \le 5$	$5 < A$
Lethal	← All voltages greater than for the "possibly lethal" class →						
Possibly Lethal							
a. Ventricular Fibrillation[++]	$150 \le V < 400$	$150 \le V < 400$	$150 \le V < 270$	$115 \le V < 210$	$100 \le V < 210$	$90 \le V < 160$	$80 \le V < 145$
b. Asphyxiation[+++]	$90 \le V < 150$	$90 \le V < 150$	$55 \le V < 150$	$40 \le V < 115$	$35 \le V < 100$	$30 \le V < 90$	$25 \le V < 80$
Painful Shock	$60 \le V < 150$	$35 \le V < 150$	$25 \le V < 150$	$15 \le V < 115$	$15 \le V < 100$	$10 \le V < 90$	$10 \le V < 85$

\+ The table classifies the range of voltages, measured from ground, according to the contact area of the component. The range of contact areas is arbitrarily divided into intervals of 1 sq. cm. and arbitrarily ends at 5 sq. cm. because it is expected that larger contact with live components will be uncommon. The ground contact area is assumed to be 150 sq. cm.

++ A discordant beating of the heart; usually it is rapidly fatal.

+++ Applies only in cases in which it is likely that a victim will become "frozen" to the circuit.

* Terminals that are used as test points should have adequate barriers between adjacent terminals to prevent accidental slipping of the probe, which could possibly cause the technician to contact high voltages. (Figure 4-21) $(1_s\text{--}1_v, 1_c)$

* Nonsparking tools are provided for use in an explosive atmosphere. $(3_s\text{--}1_c)$

23. Safety (Equipment Protection)

* When ammeter phone jacks are used, they should be of the "make-before-break" type. This will insure that circuits are not interrupted when the ammeter is connected. Circuit interruptions could remove biasing voltages and burn out tubes or cause relays to drop out. $(3_s\text{--}1_c)$

* When test jacks are located on external surfaces, jack covers should be used, where possible, to keep out moisture and dirt. $(1_s\text{--}1_v, 1_c)$

* Test points (except ammeter phone jacks) should be so located that all measurements are made with respect to ground. This is to prevent impressing voltages on the cases of some voltmeters. (1_s)

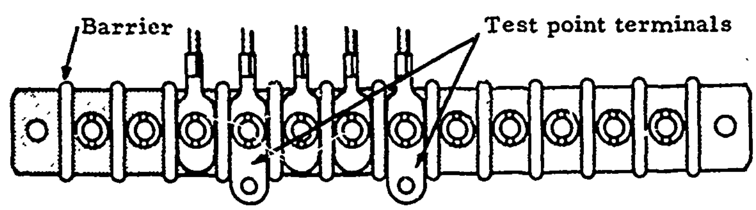


Fig. 4-21. Terminal block.

III. SIDE EFFECTS OF DESIGN FOR MAINTAINABILITY

1. Introduction

Thus far, down time reduction through design for maintainability has been the theme of this section. Although the effectiveness of various design techniques in achieving this goal has already been emphasized and some of the space, cost, and reliability trade-offs have been indicated, a note of caution is necessary concerning possible side effects of design upon other factors within the total maintenance and support picture. Design practice which is effective in reducing down time may adversely affect such maintenance-related factors as number of spare parts, volume of spares storage space, amount of test equipment, and technician training and manpower requirements. Trade-offs between design for down time reduction and its effect on these related areas cannot be ignored. This section presents several examples to demonstrate the effects of maintainability design practice upon the total maintenance and support picture for a given equipment.

2. Equipment Modularization

The relationship between equipment down time and variation in the total number of modules (n) into which an equipment is subdivided will be demonstrated first. Since a given equipment functionally requires a more or less fixed number of basic circuit elements, a change in n will generally result in an inverse variation in the size, complexity, cost, and failure rate of each of the n modules. This effect thus implies a change in the level of repair or replacement as a result of varying n. The following assumptions are made: 1) troubleshooting time is the primary determinant of down time; 2) equipment failure rate is apportioned equally among each of the n modules; 3) average time per troubleshooting step (τ) is 10 minutes; and 4) the average number of steps required to find the trouble by the most efficient (e. g., "split-half") technique is $\log_2 n$.

Thus, mean troubleshooting time (T_S) is given by the following equation:

$$T_S = \tau \log_2 n$$

The relationship between down time and degree of modularization is plotted in Figure 4-22 for τ = 10 minutes. From the equation and the graph, it is evident that a reduction in either or both number of modules (n)

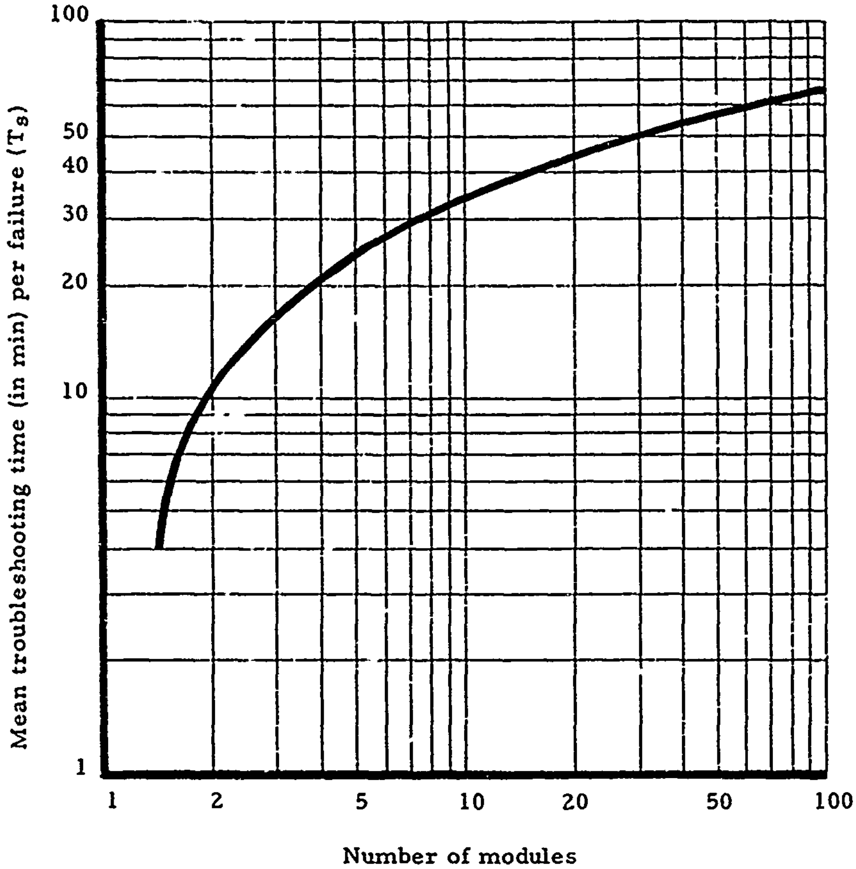


Fig. 4-22. The relationship between down time and degree of modularization.

and average time per troubleshooting step (τ) will bring about a reduction in mean troubleshooting time for the equipment, although the results will be more sensitive to τ than to n. (This point will be discussed in a slightly different context in the subsection "Test, Checkout, and Repair Time Requirements," page 307.)

Suppose it is decided to vary the degree of modularization (n) in an attempt to reduce down time. The side effects of such a decision upon spare parts, spares storage space, and logistics requirements will be demonstrated next.

Let: λ_1 = mean failure rate for over-all equipment (failures per day)

t = number of consecutive days during which equipment must be operative

n = number of modules into which equipment is subdivided (the maintainability design practice variable, in this example)

λ_i = λ_1/n = mean failure rate of i^{th} module

v_1 = volume (storage space) of over-all equipment

v_i = V_1/n = volume (storage space) of i^{th} module

s_i = number of i^{th} type modules required to provide 100% assurance that spares will not be exhausted by the end of time t. (Note: the number of spare i^{th} type modules is thus given by $s_i - 1$.)

E_i = expected number of i^{th} type module failures in time t

Under the simplifying assumption of an exponential distribution of module time-to-failure, the expected number E_i of i^{th} type module failures in time t is given by:

$$E_i = \lambda_i t$$

For the purposes of this example,

let: $t = 90$ days

$n = 1$ module

$\lambda_1 = 0.11$ failures per day

Then $E_1 = 10$ failures in 90 days for the over-all quipment. Entering any table of the Poisson distribution function with this expected value, we find that a minimum of 24 modules (total equipments in this case, since $n = 1$) is required to give 100% assurance that at least one will still be available for use at the end of $t = 90$ days (that is, $s_1 = 24$).

The total storage space required in which to store $(s_1 - 1) = 23$ spares is then given by $(s_1 - 1)\, v_1$, or $23\, v_1$.

In the same way, it is possible to determine the total number of spare parts and the total amount of spares storage space required for an equipment which is subdivided into n modules (i. e., $n > 1$). The results of such a "total spare parts analysis" are plotted in Figure 4-23 for two alternative boundary-condition assumptions.

a. All modules uniquely different (i. e., no standardization)

b. All modules identical (i. e., complete standardization)

The scale of the ordinate indicates the total number (items) of spare modules required to support a device whose failure rate is $\lambda_1 = 0.11$ for a $t = 90$-day period. The plotted curves indicate clearly the effect of degree of modularization upon the logistic support problem. (In practice, of course, the true relationship must lie somewhere between the two curves.) The total number of spares required can always be traced further to include effects on support system requirements such as paper work, transportation, work load, and so forth.

The side effects of modularization on storage space requirements are quite different in nature. The results of a "spare parts storage space analysis" based upon the foregoing assumptions are presented in Figure 4-24, with the same two alternative assumptions concerning standardization. In this instance, the scale of the ordinate indicates the total storage space required for spare modules, expressed as per cent of that space required for

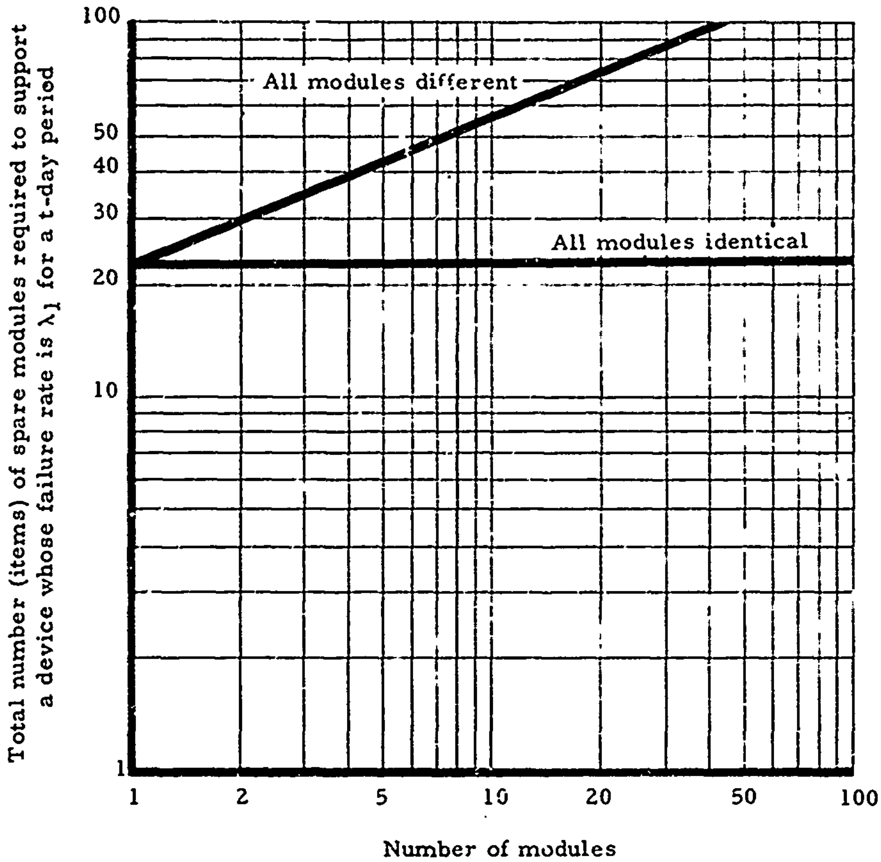


Fig. 4-23. The relationship between total number of spares required to support a device and degree of modularization.

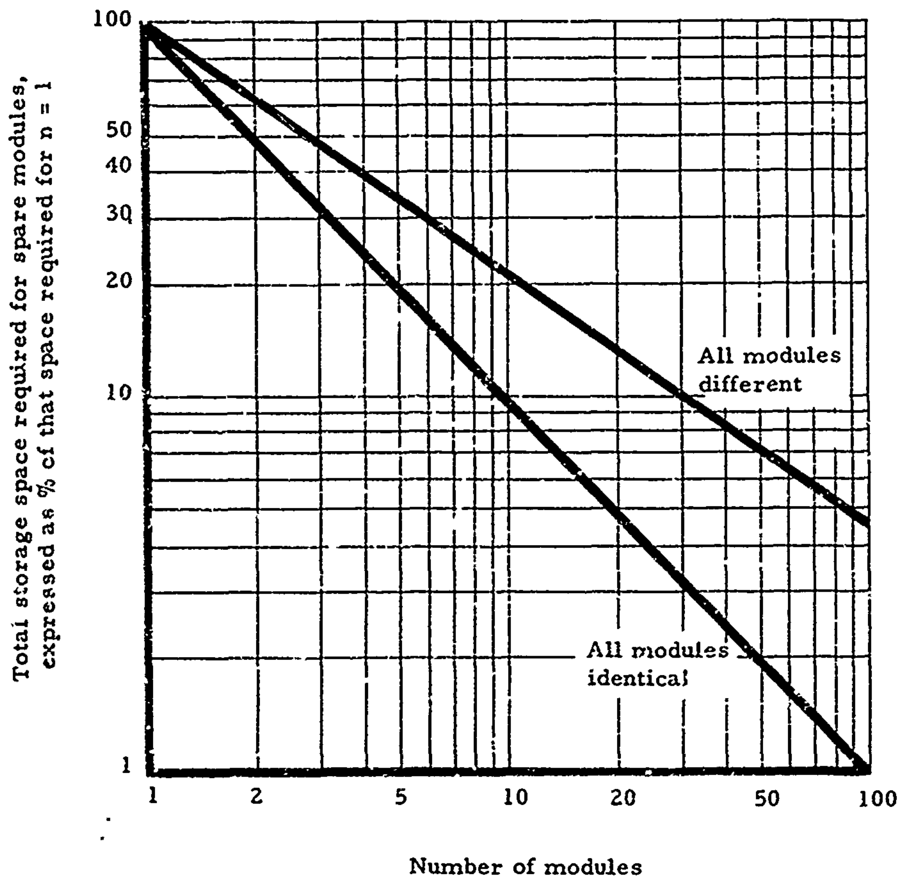


Fig. 4-24. The relationship between spare parts storage space requirements and the degree of modularization.

n = 1. The plotted curves indicate a reverse relationship with n. That is, as degree of modularization increases, total spares storage space required decreases. It may, at first glance, seem surprising that total storage space decreases while total number of spare parts generally increases with greater modularization. This is due to a nonlinear relationship between n and s related to properties of the Poisson distribution function.

The different and conflicting functional relationships that exist among spares requirements, space requirements, troubleshooting time, and number of modules indicate that the optimum degree of equipment modularization depends upon the specific operational and physical constraints which are imposed on the system requirement. For example, more consideration would be given to the space limitation if the equipment being modularized was to be used aboard the submarine than for a shipboard or land-based installation.

3. Test, Checkout, and Repair Time Requirements

The time required to test and to repair a module has a particularly significant effect on the number of men and test equipments needed to achieve any given level of equipment availability. A design-engineering effort that minimized equipment checkout time could contribute significantly to many aspects of maintainability, in addition to reducing down time. For example, an item of semiautomatic module test equipment was recently added to the Polaris Weapon System. A study investigated the economic trade-offs between several variables as a result of the introduction of this equipment.[4] The assumed constraints for this study are:

a. 2 depots

b. 45 submarines

c. $200 cost per module

d. $150,000 cost per semiautomatic tester

The relationships among five key variables are shown in Figure 4-25.

In Figure 4-25a, the interactions among three variables are considered as follows: Given alternative average module repair times of 30 min and 10 min, the total number of men required for checkout and repair is plotted as a function of average time required for semiautomatic test and checkout of a module. The data show that checkout time has a significant effect on technician manning requirements.

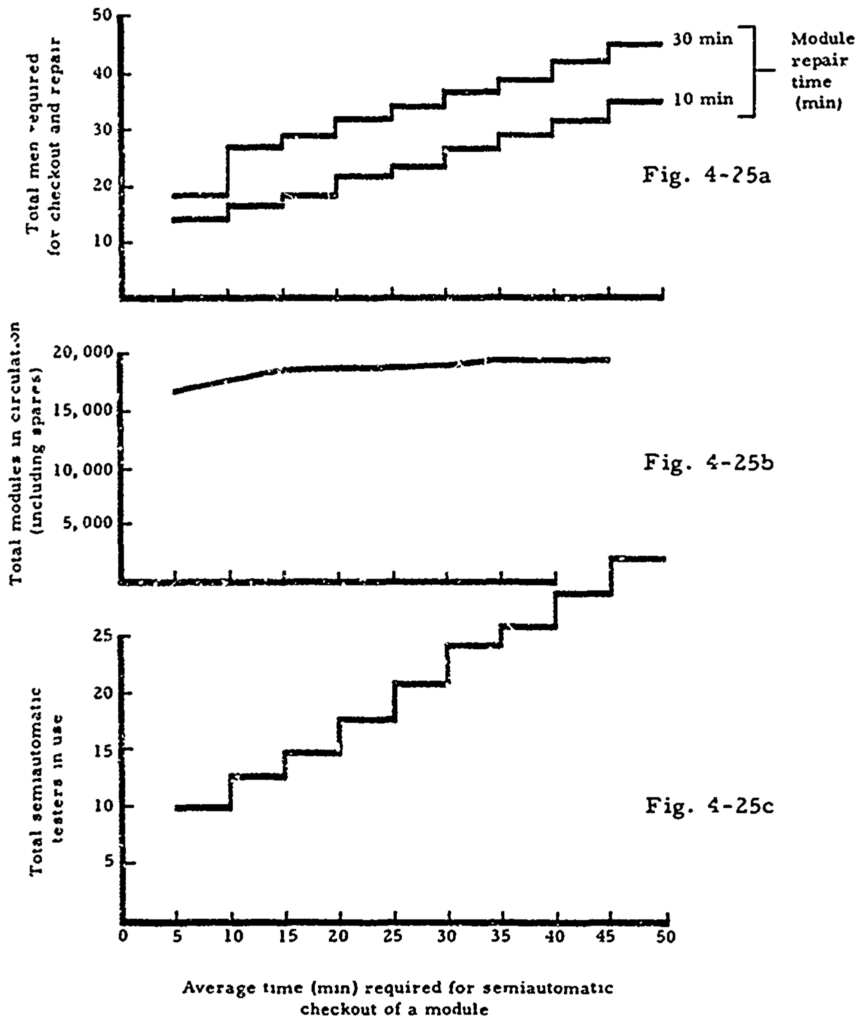


Fig. 4-25. The relationship between module checkout time and several other variables.

Figure 4-25b indicates the total spare modules in circulation as a function of average time required for checkout. The flatness of this curve shows that checkout time has relatively little effect on the total number of spares in circulation, particularly when this time is greater than 15 min.

The total number of semiautomatic module testers in use, as a function of average time required for semiautomatic checkout of a module, is shown in Figure 4-25c. Because of the large cost of these units, the curve represents a significant effect.

Thus, the data demonstrate the effects of module test time upon the requirements for men, spare modules and test equipment. A design-engineering effort which minimizes both checkout time and repair time is clearly one approach to the achievement of any given level of equipment availability.

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